

Developing a method to monitor thermal discomfort response variability

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I, Stephanie Gauthier, confirm that the work presented in this thesis is my own.

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London, May 3, 2015

Abstract

The need to identify occupants behavioural-responses to thermal discomfort during the heating season has become one of the priorities in the quest to reduce energy demand. The current models have long been associated with peoples behaviour by predicting their state of thermal comfort or rather discomfort. These assume that occupants act upon their level of discomfort through two types of responses: involuntary mechanisms of thermoregulation, and behavioural-responses. This research seeks to investigate the variability of occupant self-reported and observed behavioural-responses in residential buildings during the heating season.

The first part of the research reviews the current standard models and reports on a global sensitivity analysis of the models as described in standards and guidelines. The predictive models appear to be most sensitive to the personal variables, metabolic rate and thermal insulation of clothing. In field studies these personal variables are often estimated with a significant degree of error, and in building simulation studies they are given constant values as a function of the season and the building or room types. To address these two issues, this research introduces a mixed-method framework drawn from psychological and physiological studies. Twenty residents living in nineteen dwellings were monitored over a period of ten consecutive days, in the South-East of England during the winters of 2012 and 2013. Results from this experimental investigation enabled probability distributions for the two personal variables to be drawn. When combining the estimated activity and clothing levels with the environmental monitoring results, the predicted mean votes are substantially below those assumed in standards. This suggests that occupants in this study may be engaging in other adaptive behaviours, not currently accounted for within the standard models.

The second part of the research focuses on identifying these adaptive behaviours. One of the key issues is to gather accurate measurements while using discreet observatory methods to have minimum impact on peoples behaviour. Drawing methods from thermal comfort research and psychology, the empirical study undertaken also allows for the creation of a three-tiered framework mapping behaviour-responses to cold sensations, consisting of (1) increasing clothing insulation level, (2) increasing operative temperature by turning the heating system

on/up, and (3) increasing the frequency, duration and/or amplitude of localised behaviour responses, including for example warm food or drink intake, changing position, changing location within the same room or changing room. Using content analysis and automated segmentation, occupant-self-reported and observed diary responses to cold thermal discomfort were compared, with results showing a marked difference between them.

Theoretically, this research introduces a framework to monitor thermal discomfort responses that incorporates a wider range of observed behaviours. Methodologically, this research demonstrates the efficacy of multi-method observational approaches for understanding discomfort responses. Substantively, this research highlights the need for researchers working in this field not to fall into the gap between what occupants say and what occupants do.

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Chapter 1

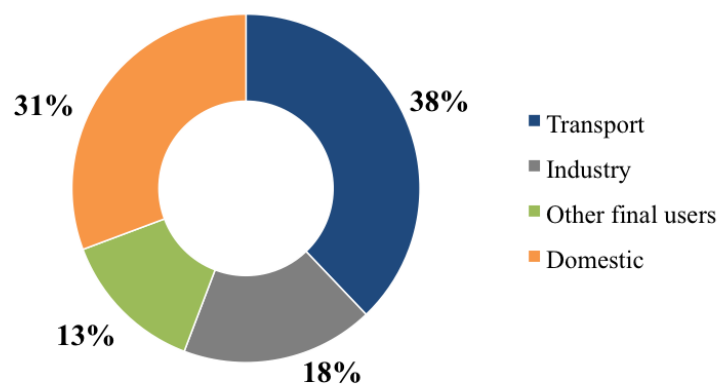
Introduction

1.1 Context and Relevance of Research

1.1.1 Energy consumption: heat demand in UK dwellings

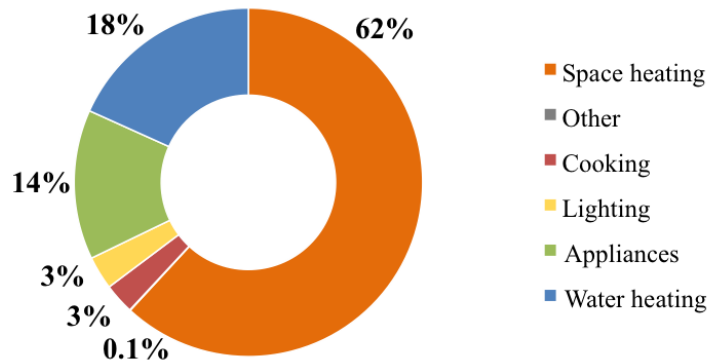
Throughout the heating season, indoor temperature is one of the most influential determinants of energy use in buildings. As of 2012, the domestic sector was responsible for approximately 31% of the total energy consumption in the UK, corresponding to 43,153 thousand tonnes of oil equivalent, as shown in figure 1.1 (DECC, 2013a).

Figure 1.1: UK energy consumption in 2012 broken down by final user (Total: 140,6 million toe) (Modified from DUKES 1.1.5, DECC 2013a)



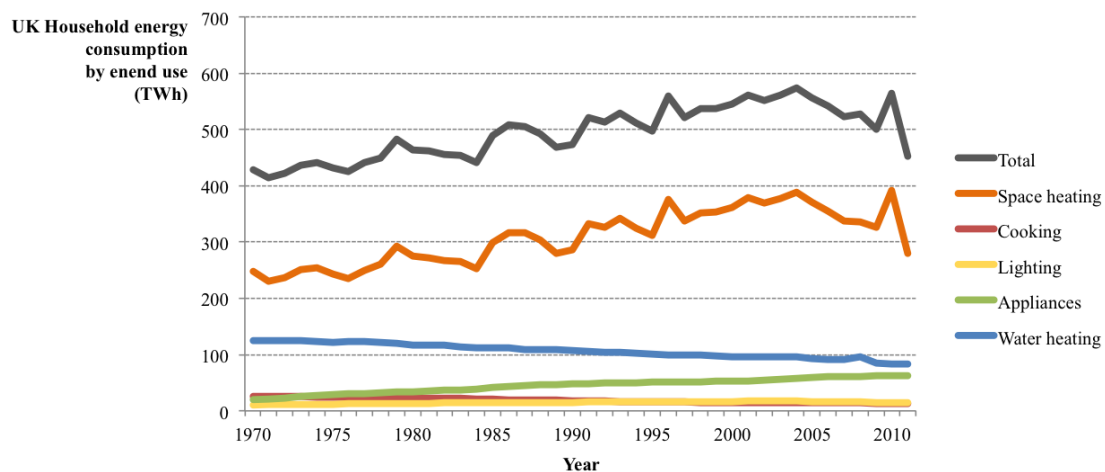
Space heating accounted for 62% of the UK's total domestic energy consumption in 2011, with another 38% being attributed to domestic hot water, cooking, lighting and appliances, as shown in figure 1.2 (DECC, 2013c). Therefore strategies aiming to reduce domestic space heating form a significant contribution towards the national commitment to reduce CO₂ emissions, as set out in the 2008 Climate Change Act (CCC 2008).

Figure 1.2: UK household energy consumption in 2011 broken down by end use (Total: 452 TWh) (Modified from Charts 5b, 5c, 5d, 5e, and 5f, DECC 2013b)



As can be observed in figure 1.3, overall residential energy consumption has increased by 5.4% between 1970 and 2011; concurrently the share of space heating has increased by 12.9% (DECC, 2013c). This change is mainly attributed to population increase, in conjunction with a downward trend towards smaller households (DECC, 2013c). Following changes in Building Regulation Approved Document L in April 2005 - mandatory efficiency levels for new boilers, a 24.5% decrease in space heating energy consumption is observed. This may also be attributed to the economic recession. Energy used for space heating increased in 2010 is observed, this may be explained by the very cold winter weather, followed by a relatively mild winter in 2011.

Figure 1.3: UK household energy consumption by end use from 1970 to 2011 (Modified from Chart 2a, 5b, 5c, 5d, 5e, and 5f, DECC 2013b)



Also it is important to highlight that in DECC (2013c), space heating, hot water, lighting and appliances energy consumption are based on modelling using BREHOMES until 2009 and then Cambridge Housing Model. This change in models may also be the caused of the sudden increase in 2010.

Whilst new buildings will play an important role in the transition from an energy intensive state to a more sustainable one, the residential stock demolition rate is very low, less than 1% per annum. At this rate, more than 60% of the 27.3 million existing dwelling will still be standing in 2050 (DECC, 2013c). Taking this into consideration, it is clear that reducing energy consumption will require interventions to the existing domestic building stock through both physical interventions, and through managing socio-cultural expectations of thermal comfort to minimise demand. A number of programs of intervention have recently been introduced. These are intended toward:

- Energy efficiency measures or building retrofit intervention through mechanisms such as the Green Deal aiming to improve the building fabric, to upgrade services, and/or to integrate renewable energy technologies.
- Consumer feedback on energy consumption including detailed bills (indirect feedback), smart meter (direct feedback), or Energy Performance Certificate (EPC).

However, unintended consequences of energy efficient solutions should be considered. These may include anticipated energy savings from retrofit failing to be realised in whole or in part as described by Sorrell, S. and Dimitropoulos, J. (2008). It is argued that this take-back or re-bound effect is partly caused by change(s) in practices; the householder may chose to turn up the heat, leave the heating on for longer, heat more rooms and/or increase the spatial average temperature. This issue has been identified as a key area for policy (DECC, 2013c). In order to tackle the rise in space heating energy consumption, it is important to map people's responses toward thermal discomfort during the winter season.

1.1.2 Health and wellbeing

Most people have a thermal expectation associated to a place, a time of day, and a season (Shove, E., 2003). For example when being at home one expects a range of temperatures, and will respond according to this expectation in order to be thermally comfortable; i.e. a householder may wear slippers as s/he expects a cold draught from uninsulated timber floor. These thermal expectations condition what individuals find to be thermally comfortable in different contexts, thus making thermal comfort a function of the social and physical characteristics of place and memory, as well as environmental and personal factors. The ASHRAE standard 55 (ASHRAE, 2013) defines the basis of the thermal comfort of a person as '*that condition of mind which expresses satisfaction with the thermal environment*'. This definition touches on psychological or psychosocial issues that characterise people's state of thermal comfort or discomfort. Responses to this state are of three kinds:

- Involuntary physiological mechanisms of thermoregulation, which aim to maintain a constant body temperature, with an average core temperature of 37°C (Parsons, K., 2003). These physiological processes are the basis of the heat balance principles and indices used in Fanger, P. (1970). Although this heat balance equation can only be validated in steady-state condition, it gives information as to how environmental variables are combined to create optimal thermal comfort. Mechanisms of thermoregulation are dynamic; in other words it refers to a person system acclimatising over a period of days or weeks as a response to changes in their environments.
- Voluntary behavioural adjustments or action response, where the occupant chose to act upon their level of thermal discomfort; for example one might decide to put a jumper on, to have a warm drink, to close the window, or to turn the room thermostat up. According to Brager, G. and de Dear, R. (1998), these types of responses may be categorised in three sub-groups: personal, technological or cultural adjustments. These three responses provide immediate and conscious feedback loops. The actions, outcomes or attained thermal comfort level will serve as a starting point in the response process. Within dwellings, the environment will provide different opportunities and constraints, which will influence the type of response(s) (Humphreys, M., 1994).
- Habituated behaviour, which influence occupants' perception of and reaction to thermal discomfort (Glaser, E., 1966). For example, external conditions can have a direct effect on thermal responses, as these may be conditioned by past experiences. In Helson, H. (1964), a review of adaptation-level theory, habits may be the result of three different

sets of operations: bipolar response (1), sets of assumptions (2) or judgement based on a skew level of central tendency or anchor (3). Habituated behaviour and expectation act as a by-pass for the choice of responses. These choices are reinforced by the degree of performance of the outcome.

Most of the studies investigating these three kinds of responses have been carried out in controlled environments or non-domestic settings where people have limited options to thermal adaptations (Tweed, C., et al., 2014). In contrast people have greater range of opportunities to change their local environment within their home. Recent studies set in dwellings have employed qualitative or mixed-method approaches to investigate thermal comfort practices in winter through sociological and ethnographic perspectives (Shove, E. et al., 2008). In the UK most studies on comfort practices, have focused on the elderly or on the impact of new technologies such as heat-pump (Hinton, E., 2010). The study by Hitchings, R. and Day, R. (2011) reveals how older people are planning to manage warmth in winter at home, in particular when applying '*common sense*' and when '*hosting and guesting*'. In summary, if feeling cold, a person may take actions to make his or herself warmer and more comfortable. However, it is important to mention that people may not be able to alleviate cold thermal discomfort. In the UK, excess mortality rates are observed during the winter season, and 'fuel poverty' has been identified as a key contributor. As the cost of energy is likely to increase in the future the excess winter deaths might also increase (Roaf, S. et al., 2009).

1.1.3 Standards and guidelines

As energy consumption and the thermal comfort of residents are closely linked to indoor temperature levels, when refurbishing or building a house, the design team should consider what indoor temperature range to aim for. Standards and guidelines provide environmental target references for intended use of space, and suggest methods to predict occupants' level of thermal comfort. Environmental target references are as follows:

- The World Health Organisation has suggested that '*optimum air temperature for residential room should be 20-22°C*' (WHO, 1988, p154).
- Public Health England has recommended 21°C as the minimum daytime temperature for rooms occupied during the day, and 18°C as the minimum night time bedroom temperature (PHE, 2013) (p6).
- In the UK, CIBSE Guide A recommends comfort criteria for specific applications incorporating activity and clothing levels. Dwellings should achieve the recommended temperature ranges set in the Table 1.1 (CIBSE, 2006).

Table 1.1: CIBSE Guide A (2006) Recommended comfort criteria for specific applications

Room type	Winter operative temperature range for stated activity and clothing levels		
	Temperature (°C)	Activity levels (met)	Clothing levels (clo)
Bathrooms	20-22	1.2	0.25
Bedrooms	17-19	0.9	2.5
Hall, stairs, landings	19-24 ¹	1.8	0.75
Kitchen	17-19	1.6	1.0
Living rooms	22-23	1.1	1.0
Toilets	19-21	1.4	1.0

¹ Based on PMV of ± 0.5

These environmental target guidelines are based on professional experience. However there has been a limited amount of field studies to verify these assumptions. This issue has been identified as a key area for research (Lomas, K. Kane, T., 2012). To complement these targets, methods to predict occupant's level of thermal comfort have been developed; these are currently divided in two approaches:

- The heat balance approach is based on physical and physiological properties. The most notable models are the Fanger model (one-node) (Fanger, P., 1970), the Pierce model (two-nodes) (Gagge, A. et al., 1986), and the Kansas State University model (two-nodes) (Azer, N. Hsu, S., 1977). These differ in the physiological models employed and the criteria used to predict thermal sensation. These models are used in ASHRAE 55 (Fanger and Gagge models), EN15251 (Fanger model), and ISO 7730 (Fanger model). This approach should be applied to mechanically conditioned buildings (heated and/or cooled), and aim to provide a uniform environment.
- The adaptive approach derives from empirical studies; it assumes that occupant preferred indoor temperature varies with external temperature, and people's behaviour changes according to the different seasons. Also, occupants are given time and opportunity to adapt, through opening and closing of windows and/or doors, modifying their activity, etc. Intended for naturally ventilated buildings, this approach is described in Standard 55 (ASHRAE, 2013) and the EN 15251 (?).

As reviewed in this sections, there is a balance to be established between reducing UK domestic energy demand for heating and maintaining occupants' thermal comfort in winter. This balance is in large part influenced by the question *What do people do to warm-up when*

they become too cold at home? This simple question is surprisingly hard to answer, as most of what people do is done out of habit, and they find it difficult to reliably remember and describe these habits. It is also hard because how cold one feels depends on personal and environmental variables. Therefore, a key element is the methodological framework employed to identify responses to thermal discomfort.

1.2 Problem Statement

The main scope of this thesis is to explore how people respond to cold thermal discomfort, in particular their behavioural responses in their home. The problem statement of the thesis was formulated as follows:

The Climate Change Act (2008) stipulates in law that the UK is aiming to reduce its overall carbon emissions by 80% from their 1990 levels by 2050. Reducing energy consumption in dwellings, in particular space heating, is an important component of meeting this commitment, as it represents 17% of the UK's total energy consumption. Although there is a considerable body of research on assessing householders levels of thermal comfort, there have been few quantitative empirical studies assessing how occupants respond to cold thermal discomfort and how such responses vary.

The research presented in this PhD thesis aims to explore the variability of people's responses to cold thermal discomfort in a dwelling. In order to address this complex issue, it was important to develop an innovative and tailored approach, that drew on subjective and objective methods. Fundamentally it is based on a longitudinal analysis of participants and their behaviours; however it is believed that the methods applied in this thesis could be transferable to different settings and seasons. To follow the problem statement, the research question was devised as:

How are people responding to cold thermal discomfort in their homes?

The scope of the research is delineated by three parameters. Firstly, the study is focusing on dwellings. The housing types monitored are typical of those found in England although not statistically representative. Secondly, the study is limited to cold thermal discomfort response in winter. Thirdly, the study is limited to the analysis of thermal comfort and thermal discomfort response. In seeking to answer this research question a multidisciplinary approach, drawing on methods from the built environment sciences, physiology and psychology has been developed. The development of the mixed-method approach used in this thesis lends itself to a quantitative and qualitative assessment of case-studies. This mixed-method approach could be expanded in the future to address post-occupancy assessment and domestic energy demand projections.

1.3 Aims and Objectives: Program of Work

In order to address the above problem statement and research question, four main objectives have been identified.

- In order to understand the comparative importance of the different influences on thermal comfort embodied in existing approaches, an evaluation of the global sensitivity of the models described in standards and guidelines will be undertaken. This will identify the factors that should dominate householders cold thermal discomfort response, and therefore which factors should be most accurately and precisely measured in the empirical study.
- Currently, methods do not exist to measure two personal variables, metabolic rate (M) and clothing insulation (I_{cl}), objectively and quantitatively, therefore development of methods to estimate these variables in free living environment is required.
- A set of methods to gather people's responses to thermal discomfort in free-living environment at a fine temporal resolution is needed.
- Empirical findings will be incorporated into a framework to monitor thermal discomfort responses that incorporates a wider range of observed behaviours.

The concluding aim of this research is to help rethink the ways thermal comfort in the home can be maintained while reducing space-heating energy consumption.

1.4 Thesis Structure

This thesis has been structured to follow the chronological development of the work in two parallel strands, set as: (a) the estimation of activity and clothing level as objective, quantitative and continuous variables, and (b) the monitoring of people's cold thermal discomfort responses.

The thesis is organised in the following way:

- **Literature review chapter**

Chapter 2 gives an overview of the research setting, and current knowledge in the field, in particular:

- The impact of cold on comfort, health and energy demand in UK's dwellings.
- People's responses to thermal discomfort, in particular (a) thermal physiology, (b) physiological adaptation, and (c) behavioural responses.
- Thermal comfort practices in winter: sociological and ethnographic perspectives.

- Detailed summary of human thermal comfort models.
- Measurement and assessment methods: (a) summary of current approaches, methods and techniques, and (b) key studies undertaken to date.

- **Methodology and results chapters**

Chapter 4 reports on an evaluation of the sensitivity of the thermal comfort models. Then methods to estimate activity and clothing level are discussed, followed by the results of an empirical study. The chapter includes the following sections:

- Sensitivity analysis of the thermal comfort models.
- Review of method to evaluate activity and clothing level.
- Empirical study - Results and analysis.

Chapter 5 proposes a method to capture people's cold thermal discomfort responses, and reports on the results of empirical studies. The chapter includes the following sections:

- Review of methods to capture people's cold thermal discomfort responses.
- Pilot field study - Results and analysis.
- Main field study - Results and analysis.

- **Discussion chapters**

Chapter 6 discusses the results, reviews the internal and external validity of the research, and introduces a framework to monitor thermal discomfort responses in UK's homes.

Chapter 7 summarises the combined findings, lists their limitations and caveats, examines their implication for standards and finally offers recommendations for future research.

1.5 Papers from this thesis

The research presented in this thesis was funded by UK Engineering and Physical Sciences Research Council (EPSRC) support for the London-Loughborough Centre for Doctoral Research in Energy Demand, grant number EP/H009612/1. The study had an input into one book chapter, two peer-reviewed journal papers, two peer-reviewed conference papers published in journals, and seven peer-reviewed conference papers published in conference proceedings. The role of the author of this thesis in each publication is indicated below, in conjunction with the thesis chapters. Copies of all papers are provided in Appendix D.

Important note: For concision the papers included in the Appendix represent additional work, not necessarily contained within the main thesis document. They include further work on the review of literature, methods' validation, and building simulation modelling.

1.5.1 Book chapter

1. Ucci, M., Gauthier, S., Mavrogianni, A. Thermal Comfort: Assessment, Psychosocial Aspects and Health Impacts. A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health, and Operational Performance. Editors: Mumovic, D., Santamouris, M. Earthscan, London. (Submitted 9th May 2014)
Contribution to the chapter: literature review of methods to assess thermal comfort, and writing-up.
Relevant PhD chapters: Chapter 2, 4 and 5 (review of methods).

1.5.2 Peer-reviewed journal papers

1. Gauthier, S., Shipworth, D. (2015). Behavioural responses to cold thermal discomfort, Building Research & Information, 43:3, pp.355-370.
Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an in-depth review of the draft and final version.
Relevant PhD chapters: Chapter 4, 5 and 6 (results and analysis).
2. Spataru, C., Gauthier, S. (2013). How to monitor people smartly to help reducing energy consumption in buildings? Architectural Engineering and Design Management, 10(1-2), pp.60-78. *Contribution to the paper:* literature review of wearable sensors, data-collection using SenseCam, heart-rate monitor and environmental sensors, analysis and writing-up.
Relevant PhD chapters: Chapter 4 and 5 (review of methods).

1.5.3 Peer-reviewed conference papers published in journals

1. Gauthier, S., Shipworth, D. (2013). Review of Methods to Map People Daily Activity: Application for Smart Homes. In A. Hakansson et al., eds. Sustainability in Energy and Buildings, Springer Berlin Heidelberg, Volume 22, pp. 401-411.
Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an general review of the draft and final version.
Relevant PhD chapters: Chapter 4 (review of methods).
2. Gauthier, S. (2012). Mapping Occupants Thermal Discomfort Responses in Households Using SenseCam. In N. MSirdi et al., eds. Sustainability in Energy and Buildings, Springer Berlin Heidelberg, Volume 12, pp. 437-445.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up.

Relevant PhD chapters: Chapter 4 and 5 (literature review, results and analysis).

1.5.4 Peer-reviewed conference papers published in conference proceedings

1. Gauthier, S. Shipworth, D. (2014). Generating empirical probabilities of metabolic rate and clothing insulation values in field studies using wearable sensors. Conference proceedings: 13th International Conference on Indoor Air Quality and Climate, 7-12 July 2014, Hong Kong.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an general review of the draft and final version.

Relevant PhD chapters: Chapter 4 (review of methods, results, and analysis).

2. Gauthier, S. Shipworth, D. (2014). Variability of thermal stratification in naturally ventilated residential buildings. Conference proceedings: 2014 Building Simulation and Optimization Conference. 23-24 June 2014, London, UK.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an general review of the draft and final version.

Relevant PhD chapters: Chapter 2 and 5 (monitoring and modelling).

3. Gauthier, S. Shipworth, D. (2014). The gap between what is said and what is done: a method for distinguishing reported and observed responses to thermal discomfort. Conference proceedings: 8th Windsor Conference: Counting the Cost of Comfort in a changing world Cumberland Lodge, Windsor, UK, 10-13 April 2014. Network for Comfort and Energy Use in Buildings. London, UK.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an general review of the draft and final version.

Relevant PhD chapters: Chapter 5 and 6 (review of methods, monitoring, results and modelling).

4. Gauthier, S. M. (2013). The role of environmental and personal variables in influencing thermal comfort indices used in building simulation. Conference proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up.

Relevant PhD chapters: Chapter 4 (literature review and analysis).

5. Gauthier, S. Shipworth, D. (2012). Predictive thermal comfort model: Are current field studies measuring the most influential variables? Conference proceedings: 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World, Cumberland Lodge, Windsor, UK, 12-15 April 2012. Network for Comfort and Energy Use in Buildings. London, UK.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up. The co-author carried-out an general review of the draft and final version.

Relevant PhD chapters: Chapter 4 (literature review and analysis).

6. Gauthier, S. M., (2011). What Are People's Responses to Thermal Discomfort? Sensing Clothing and Activity Levels Using SenseCam. UC Berkeley: Behavior, Energy and Climate Change Conference, USA.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up.

Relevant PhD chapters: Chapter 5 (literature review, results and analysis).

7. Gauthier, S., (2011). Understanding the dynamics of residential energy consumption: Mapping occupants thermal discomfort responses. Conference proceedings: ECEEE 2011, Summer Study, Energy efficiency first: The foundation of a low-carbon society. ABA Intercopy, Stockholm, Sweden.

Contribution to the paper: literature review, data-collection, analysis, discussion and writing-up.

Relevant PhD chapters: Chapter 5 (literature review, results and analysis).

Chapter 2

Literature review

2.1 Outline

This chapter explores the fundamental principles of human thermal comfort in cold conditions, summarises existing approaches and gives an overview of the key studies undertaken to date. The aim of this chapter is to review the theory of thermal comfort and issues that affect health within buildings, in particular dwellings.

2.2 Impact of cold on health and energy demand in UK's dwellings

Studies conducted in the United States and Europe reveal that people spend over 90% of their time indoors, and about 70% of their time at home (EPA, 1989) (Lader, D. et al., 2006). Therefore, it is important to map how people respond to thermal discomfort within their home, and the associated implications on health and energy demand.

2.2.1 Impact on health

Cold temperatures have a direct impact on the thermal comfort and health of occupants. Although people acclimatise to their local climatic conditions through physiological, behavioural, and cultural processes, exceeding cold exposure may cause clinical symptoms of cold stress, in particular hypothermia, cardiovascular and respiratory effects (International Organization for Standardization (ISO), 2001b). During winter, cold external weather is expected to decrease indoor air temperatures leading to reduced thermal comfort, increases in heating demand, and cold-related mortality. Previous studies have highlighted that between 1988 and 1997 an average of 37,000 annual excess winter deaths have been recorded in the UK. This represents an increase of 18% above the average mortality rate (Healy, J., 2003). In London, an important cold-effect is observed, as below daily mortality increase significantly in winter. In Pattenden, S. et al. (2003), this cut off point was set at the 10th centile, or 5.25°C. For a 1°C average drop below the 5.25°C, mortality in London increased by 4.24%.

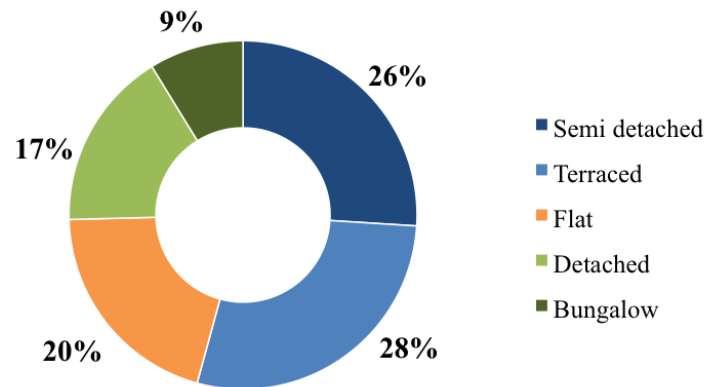
Winter mortality may be associated to fuel poverty. This socio-economic factor is defined by DECC (2012a) as a household which *'spend more than 10% of its income on fuel to maintain an adequate level of warmth - The adequate standard of warmth is usually defined as 21 degrees for the main living area, and 18 degrees for other occupied rooms'*. In 2010, there were 4.75 millions of households in fuel poverty, corresponding to 18.6% of the total amount of UK households. Fuel poverty depends on the interaction of three key factors: income, energy prices, and energy demand. It is likely that vulnerable social groups will be affected disproportionately by cold temperatures due to their inability to pay for energy to heat their home, and for energy efficiency upgrades of their dwelling. In summary, cold winters pose a significant challenge on health and well-being. Among the most affected are the elderly, the chronically ill, and the socially deprived population groups.

2.2.2 Impact on energy demand

As highlighted in the introduction, in 2009, space heating accounted for 62% of the UK's domestic energy consumption, which corresponds to 19.2% of UK's total energy consumption (DECC, 2013a) (DECC, 2013c). To reduce space heating demand, one solution would be to systematically refurbish the existing building stock. Therefore it is important to review the existing housing building composition. In 2010, there were 62.2 million people and 26.6 million households in the UK, which equate to a ratio of two occupants per household (DECC, 2013c). Looking at the trends over the last 40 years, it is interesting to note that the number of occupants per household has decreased steadily from 3 to 2 occupants per household. Energy demand is significantly associated with both population and number of households. However, space heating demand correlates more strongly with **internal demand temperature, the main heating system efficiency, external temperatures, the size of the dwellings and building fabric characteristics** (Hughes, M. et al., 2013). It is important to review each of these variables individually to establish the sample characteristics of future empirical studies.

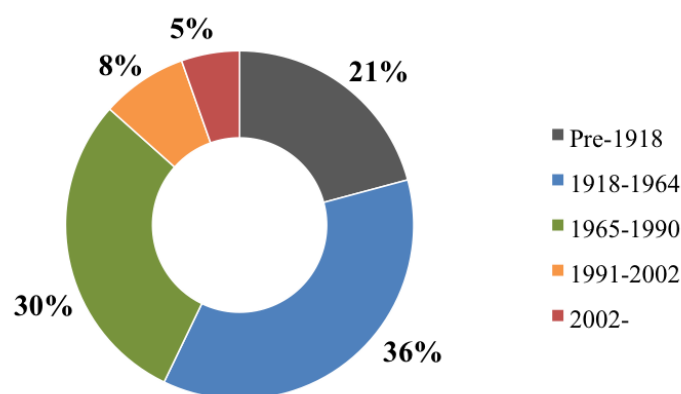
The first variable to consider is the dwelling size. In 2011, most dwellings were terraced (28%) or semi-detached houses (26%) (DECC, 2013c) (see Figure 2.1). Interestingly, 'detached', 'bungalow' and 'semi-detached' dwellings represent 52% of the stock, and have the highest ratio of exposed wall area to floor area (Brown, F. and Steadman, P., 1991), and potentially higher fabric heat loss.

Figure 2.1: UK housing stock distribution by dwelling type in 2011 (Modified from Chart 4c, DECC 2013)



The second variable to review is building fabric characteristics, which are closely related to the age of the dwelling (BRE, 2012). In 2011, most dwellings were built pre-1964, with 21% representing 5.1 million dwellings built before 1918 (DECC, 2013c) (see Figure 2.2). The external walls of pre-1918 dwellings are usually solid (BRE, 2005), which are more challenging to retrofit with insulation than cavity walls (Dowson, M. et al., 2012).

Figure 2.2: UK Housing stock distribution by dwelling age in 2011 (Modified from Chart 4d, DECC 2013)

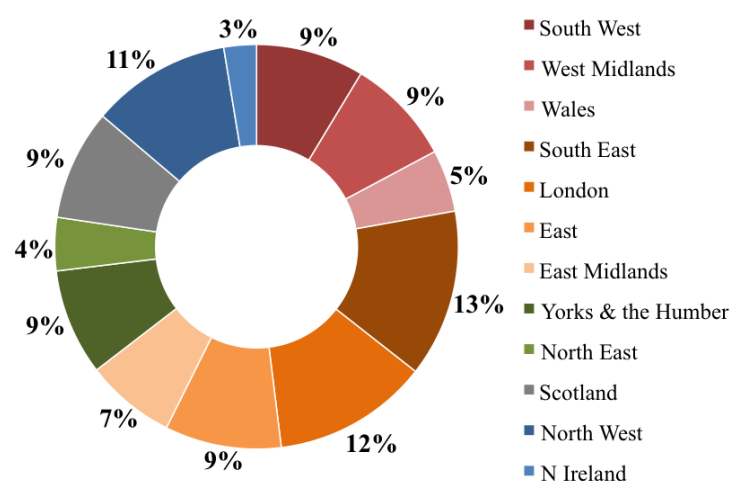


The third variable to consider is the type and efficiency of heating systems. To explore the current stock, the diffusion of the different systems should be reviewed. Historical research on heating systems in building may start with **warm-air systems** such as the hypocaust in Greek

and Roman baths where floor and, in some cases, walls were heated by warm-air and smoke from the underfloor or hollow wall-brick (Chrenko, F., 1974). Still, most homes were heated by fires, lighted on the earth floor in the centre of the room, and smoke flowed through a hole in the roof or wall openings. Vertical chimneys were introduced in England in the middle of the fifteenth century, yet smoke was an issue (Chrenko, F., 1974). One solution was to increase the draught up the chimney, the other was the development of fire-grate, and later of closed stoves. This latest innovation led to the development of **hot-water systems** by which water-pipes from a boiler were led through a circuit within the room to be heated. Emerging in the eighteenth century, this system was improved by the introduction of radiators and panel-heating (Roberts, B., 1997). In 2011, 91% of homes in the UK were heated by a hot-water central-heating system from the combustion of fuel within the dwelling (DECC, 2013c). Some homes are part of larger networks, where steam is conveyed within a group of houses or district; a system that may become more common in the future (DECC, 2013b).

The fourth variable to review is the external temperatures which vary across the UK's eleven regional climates (Met Office, 2013). As shown in Figure 2.3, 64% of the dwellings are located in the Southern regions. UK climate projections show that mean daily maximum temperatures are likely to increase across the country, potential reducing the demand for space heating (Jenkins, G. et al., 2009).

Figure 2.3: UK Housing stock distribution by region in 2011 (Modified from Chart 4b, DECC 2013)



In conjunction with external temperature and building fabric, dwellings' ventilation systems should be considered. In the UK, most dwellings are naturally ventilated using windows and stack, with intermittent extract fan. Sufficient ventilation needs to be provided for inhabitants, whilst not leading to excessive heat loss. On the one hand, natural ventilation strategies lead to significant energy savings, on the other, naturally ventilated buildings tend to be vulnerable to cooling trends (De Saulles, T., 2000), in particular when external temperature fall below the degree day of 15.5°C (Chartered Institution of Building Services Engineers (CIBSE), 2006). Daytime ventilation becomes an undesired cooling source; therefore mechanical or mixed mode heating systems may become necessary to reduce heat losses. Creating a thermally comfortable environment while reducing energy demand is one of the most important considerations when designing and refurbishing a building. For new build, there is now a focus on improving airtightness, and the introduction of mechanical ventilation systems with heat recovery (Zero Carbon Hub, 2013).

2.2.3 Summary

Cold winters have a direct impact on the health risk and energy demand of households. In particular, space heating demand is linked to behavioural factors such as the internal demand temperature, and environmental factors such as climate, dwelling morphology, building heating systems and fabric characteristics. These variables are of particular importance in the choice of empirical studies sample characteristics.

2.3 People's responses to thermal discomfort

As described in the introduction, thermal comfort refers to psychological or psychosocial issues where peoples opinions validate their state of comfort or discomfort. As described by Brager, G. and de Dear, R. (1998), people may adapt to their state of thermal discomfort through three types of mechanisms:

- Involuntary physiological adaptation: the body responds to changes within the thermal environment, this may include acclimatisation.
- Involuntary psychological adaptation: people may hold a mental-model of a specific thermal condition, it may be constructed from previous experiences, or expectations.
- Involuntary or voluntary behaviour adaptation: it includes habituated behaviours and action responses which are grouped into three categories; personal, technological, and cultural adaptive behaviours.

By applying analytic hierarchy process (AHP) to case studies conducted in the UK and China, Liu, J. et al. (2012) have developed a method to quantify the proportion of these responses in the adaptation process. Results of this analysis show that participants in the UK tend to first apply physiological (51%), then psychological (26%) and finally behavioural adaptation (24%). Although these results are based on the subjective assessments of 41 experts and academics, they allow to better understand and quantify the interaction between each response-type. The following sections will first describe in detail the 3-types of adaptive responses, then it will review thermal comfort practices in winter through sociological and ethnographic perspectives.

2.3.1 Human thermal physiology

For health and well-being, the core body temperature of 37°C is maintained at an almost constant state irrespective of different environmental conditions (Parsons, K., 2003). The process of maintaining this equilibrium is called thermoregulation, and is formed of two parts:

- System-A: How the human body produces and uses heat. (Physiology)
- System-B: How the heat is transferred between the human body and the thermal environment. (Physics)

The heat production should be equivalent to the heat dissipation with little heat storage within the body. This balancing mechanism is called the heat-balance.

First looking at system-A, the body produces heat by converting most of the food and drink intake into heat and work. About 25% of the energy gained in food and drink is used for conversion process. One of the six-variables of the standard predictive thermal comfort model is metabolic rate (ISO 8996:2004). As one becomes more active, the body needs to get oxygen to the muscles through the blood flow and extract oxygen from the blood to the muscles. For these two processes to occur, the blood flow will increase as well as the rate and depth of breathing. As the muscles work, heat is produced as a bi-product of metabolic reactions and excess energy from the chemical processes. To summarise, increased activity level will increase body heat and the feeling of warmth. The amount of heat produced is expressed in watts per square meter of body surface area (W/m^2), or in metabolic unit (met), where 1 met = 58.2 W/m^2 (ISO 8996:2004). The average skin surface area of an adult is set as 1.8 m^2 for a man and 1.6 m^2 for a woman or 1.7 m^2 for an adult (ISO 8996:2004); while the activity level may be estimated using heart rate and oxygen consumption. A study by Ceesay, S. et al. (1989) monitored the heart rate of twenty subjects to predict total energy expenditure. Electrodes in a chest belt recorded an electrocardiograph signal continually, later processed to estimate heart rate. A set of activities was performed during which total energy expenditure was estimated

using heart rate and oxygen consumption. Results show that heart rate and energy expenditure are closely correlated during exercise, however this relationship is weak for rest or light activity. Therefore, during sleep, energy expenditure may be estimated as the basal metabolic rate; this estimation may follow the series of predictive equations developed by Henry, C. (2005a) as a function of the subject's gender, age and weight. During sedentary activity, energy expenditure may be estimated by oxygen consumption. Following series of similar tests as Ceesay, S. et al. (1989), a compendium of 605 physical activities was established (Ainsworth, B. et al., 2000); these may be classified into 5-categories of activity level, set by ISO 8996:2004 (Table A.2) as:

- Resting, with an average power of 115 W or a metabolic rate of 65 W/m².
- Low metabolic rate, with an average power of 180 W or a metabolic rate of 100 W/m² - this includes light manual work, such as writing, drawing, driving, etc.
- Moderate metabolic rate, with an average power of 295 W or a metabolic rate of 165 W/m² - this includes sustained work, such as plastering, picking fruit or vegetables, etc.
- High metabolic rate, with an average power of 415 W or a metabolic rate of 230 W/m² - this includes intense arm and trunk work, such as sawing, digging, walking at speed, etc.
- Very high metabolic rate, with an average power of 520 W or a metabolic rate of 290 W/m² - this includes very intense activity, such as climbing stairs, running, etc.

Both systems -A and -B are balancing out using thermoregulation mechanisms to regulate the body temperature, these mechanisms follow 3-sequences (Houdas, Y. and Ring, E., 1982):

- Normal body core temperature is about 37 °C, and varies at a slower rate than skin temperature.
- If the core temperature increases above 37 °C, the hypothalamus start to action physiological cooling mechanisms, such as:
 1. Increasing the blood flow to the skin, increase in heart rate - vasodilatation.
 2. Initiating sweating mechanism - evaporative cooling.
- If the core temperature falls 34 °C, the skin sensors start physiological heating mechanisms, such as:
 1. Reducing blood flow to the skin, decrease in heart rate - vasoconstriction.
 2. Regulating muscle tension - shivering.

In the case of extreme or prolonged cold exposure, a person's health and well-being may be put at risk, as described in ISO 12894:2001 (Annex B.3). Health effects arising in cold conditions include:

- Hypothermia, defined as a core temperature below 35 °C. This is the result of a progressive fall of the core temperature. The symptoms are shivering, affecting gait and coordination. Below 32 °C symptoms become more severe, and consciousness can be lost at temperatures below 30 °C.
- Cardiovascular effects including bradycardia and an increase in blood pressure. This may be dangerous in individuals with pre-existing hypertension. Cold air inhalation may precipitate angina pectoris in some people who suffer this condition.
- Respiratory effects including asthmatic episodes, coughs, rhinitis and nose bleeds.
- Other effects including diuresis, arthritic and musculoskeletal disorders.

In summary, the impact of a cold environment may have severe consequences to the health of occupants.

Following the review of the human body's 'short-term' physiological responses, 'long-term' thermal adaptation may also take place within the occupants' lifetime and is referred to as phenotypic adaptation (IUPS Thermal commission, 2001). This adaptation may be due to changes in natural climate (acclimatisation), or if the participant was to take part in an experiment, changes in experimental environmental settings (acclimation). Both processes allow for modification of thermal tolerance through two types of responses; morphological configuration (Somero, G., 2010), and physiological or behavioural responses (Brager, G. and de Dear, R., 1998). To follow repeated stimulation, habituation may take place, and, in this case, it is defined as the reduction in responses or perception of thermal stress. With regards to cold adaptation, repeated cold exposure dampens shivering and vasoconstriction which may lead to lower core temperature. This was observed in Eskimos, fishermen and outdoor workers (LeBlanc, J., 1992). The review by Young, A. (2011) showed that habituation is the most common form of cold acclimatisation.

Focusing on people's physiological thermal responses, it includes cardiovascular responses, metabolic heat production, shivering and sweating (Mayotte, M., 1995). These mechanisms may be identified by using physiological measurements of body core temperature, local and mean skin temperature, heart rate, and body-mass loss (ISO 9886:2004). The standard predictive thermal comfort model is in part determined by core and skin temperatures, these

relationship were reviewed by Gagge, A., Stolwijk, J. and Hardy, J. (1976), where six resting unclothed male subjects were exposed to environments of 28-29 °C for 1-hour, then 17.5 °C or 48 °C for 2-hours, and finally 28-29 °C for 1-hour. In cold conditions, results show a drop in skin temperature and heart rate due to vasoconstriction where the blood shifts away from the skin. There was also a fall in core temperature measured as tympanic and rectal temperature. In warm conditions, results were very different as a skin temperature, heart rate and core temperature increased, as well as tissue conductance and evaporative heat loss; these observed results were the effect of vasodilatation and sweating. When comparing these results to thermal sensation, the sense of cold discomfort correlates best with lowering average skin temperature. Although the sample was small and the measuring instruments may not have been as accurate as currently used devices, the results were similar to a recent study conducted by Jacquot, C. et al. (2014), where sixteen female subjects were exposed to an ambient temperature of 24 °C for 45-minutes, then a gradual increase to 32 °C (+ 4K/h) or a gradual decrease to 16 °C (- 4K/h) for 2-hours. Results show that skin temperature at the wrist was the best predictor of thermal sensation.

2.3.2 Psychological responses

The second most frequent response to thermal discomfort is psychological adaptation (Liu, J. et al., 2012). The state of the environment is captured through our cognitive system and then evaluated based on past experience(s) and present contextual factor(s) (Auliciems, A., 1981). This interaction between the environment and the building occupants is part of a large body of science, environmental psychology. With regards to thermal comfort research, psychological thermal adaptation refers to 'adaptation-level theory' (Brager, G. and de Dear, R., 1998). According to this approach, stimuli are part of broader classes and not isolated events (Helson, H., 1964).

One of the fundamental issues is the "*anchoring effects*" where the intensity of initial stimuli will affect subsequent ones. A study by Vargas, G. and Stevenson, F. (2014) investigates people's short term thermal history, where people's subjective assessment of walking through lobby spaces was studied. Results show that a 1 to 2 °C rise or decrease in temperature has no significant effect on the thermal perception. Moreover, these anchors will have a residual effect in memory, and form the basis of a person's expectation. A person preferred temperature may be function of daily or seasonal changes in outdoor climate or of contextual factor (Fountain, M., Brager, G. and de Dear R., 1996). For example, one might expect that their home will be warmer than outdoor winter conditions, and occupants take their coat off when entering their home. Similarly people's clothing level is in part determined by outdoor temperature and

people's expectations from one day to the next (Morgan, C. and de Dear, R., 2003) (Schiavon, S. and Lee, K. H., 2013).

Another fundamental issue in 'adaptation-level theory' is the "*performance*" of the response to the stimuli (Helson, H., 1964). The level of the response's efficacy compared to a norm or benchmark will determine its appropriateness, and also form an association between stimuli and response. This association may be reinforced following new exposure(s), and may form habits; here habituation is defined by results from past exposure(s) (Liu, J. et al., 2012).

Finally, the third issue in 'adaptation-level theory' is the "*assimilation and contrast in sensory and social-judgemental process*" (Helson, H., 1964). This process of assimilation may be best described in the establishment and operation of mental models, cognitive models and conceptual models (Staggers, N. and Norcio, A., 1993). These are models that people have of themselves, others and the environment with which they interact (Norman, D., 1983). They may be defined and characterised by three classes: (1) knowledge structure, (2) metaphors and analogies, and (3) how users interact with complex systems (Schumacher, R. and Czerwinski, M., 1992). They are formed through experience(s), training(s) and instruction(s). Mental models are dynamically constructed by engaging with new experiences, and activating stored schema or network of general knowledge based on previous experiences (Preece, J. et al., 1994). Even if the mental models of occupants are neither complete nor accurate and differ from person to person, they still guide people's behaviour and, in this case, their adaptive responses to cold thermal discomfort. As Norman, D. (1983) suggested, through the continuous interaction with their dwelling's thermal comfort system, the occupants will continue to modify their mental model in order to find a suitable response to thermal discomfort.

In summary, the effect of past experiences on thermal discomfort may be incorporated into a psychological feedback loop model as described in de Dear, R., Brager, G. and Cooper, D. (1997) (Figure 1.5). Expectation and habituation have a direct effect on thermal sensation and assessment.

Beyond people's long and short term thermal history, contextual factors will have an effect on psychological responses. These factors include (Varges, G. and Stevenson, F., 2014):

- People's personal background - social conditions, economic considerations, etc.
- Current context - other people's responses, environmental conditions, etc.

Candas, V. and Dufour, A. (2005) reviewed the effect of environmental conditions, in particular non-tactile stimulations on thermal comfort. As the cerebral cortex contains multisensory regions, one might suggest a relationship between visual, auditory and tactile sensations.

Thermal sensation may focus on auditory-tactile and visuo-tactile integrations. Using fMRI data, Macaluso, E. (2006) studies show that the visual cortex can process tactile input for object recognition, and spacial location. The colour and intensity of the ambient lighting may also have an effect on thermal sensation (Candas, V. and Dufour, A., 2005).

Another effect of the context is the design and control of the thermal comfort systems. This touches on the concept of affordance and usability - to which extend the occupants perceive their home thermal comfort system and use it to adapt to discomfort (Gibson, J., 1979) (Tweed, C., 2009).

Most studies aiming to evaluate psychological adaptation have used social sciences methods, including questionnaires, focus groups, and observations (Heijs, W. and Stringer, P., 1988). The data collected are occupant or observer reported responses, as anecdotal evidence (Brager, G. and de Dear, R., 1998). These subjective assessments may be prone to bias - for example, the interviewee may want to 'please' the interviewer or give socially desirable responses, or the observer may interpret results inaccurately, or the sample itself may not be representative and introduce biased results (Rice, S., 1929) (Bryman, A., 2012). Recent studies have used heart rate variability (HRV) to establish different thermal comfort levels (Liu, W. Lian, Z. and Liu, Y., 2008) (Huang, C. et al., 2011). This emerging method is based on the relationship between the ratio of HRV low frequency (LF) and HRV high frequency (HF), and the balance of the autonomic nervous system; the sympathetic versus the parasympathetic system. When exposed to cold conditions, the body is 'stressed' and the sympathetic nervous system answers by controlling vasoconstriction and shivering. In Liu, W. Lian, Z. and Liu, Y. (2008) study, 33 subjects were exposed to air temperatures of 21, 24, 26, 28, 29, and 30 °C. Results indicated a relationship between reported thermal sensation and change in LF/HF ratio; in particular LF/HF ratio significantly increased when cool discomfort was reported. Considering this relationship, HRV may be used in a future study as an objective indicator for the evaluation of subjective thermal comfort levels.

In conclusion, psychological adaptation plays a key role in the human response to thermal cold thermal discomfort. Also, it might be the most significant factor in explaining the gap between observed and predicted thermal sensation (Brager, G. and de Dear, R., 1998).

2.3.3 Behavioural responses

People use behavioural adaptive strategies to cope with their thermal environment, these may be direct intentions, or embedded behaviour. In their home it is assumed that people have access to diverse coping strategies.

There are a number of adaptive strategies that occupants may choose to manage their thermal comfort level, including (Heerwagen, J. and Diamond, R., 1992) (Brager, G. and de Dear, R., 1998) (Karjalainen, S., 2009) (Hwang, R. and Chen, C., 2010) (Tweed, C., et al., 2014):

- Controlling heat sources, by reducing/increasing temperature, and radiant heat load; by adjusting thermostats, or using local heaters.
- Shielding the source of cold, by using 'barriers' such as curtains on windows.
- Controlling the air movement, by reducing/increasing draught, by closing/opening window or doors, or by using fans.
- Changing location within a room or the house; each activity might have a best-suited location to perform a task, and be thermally comfortable.
- Changing level and type of activity.
- Changing food and liquid intake, for example by having warm drinks or food.
- Adjusting clothing insulation level; multiple layers of clothing enable to make adjustments based on ones own subjective thermal sensation.
- Using localised behaviour adaptation, for example a hot water bottle.

These adaptive behaviours were identified using qualitative research methods such as interviews, "*pen-and-paper*" diary, and ethnography. Recent ethnographic studies in the UK have focus on practices what one may adopt. Interestingly one may chose to turn on the central heating to dry clothes rather than keeping warm (Pink, S., 2012). Social pressure may also play a role, for example older people may rise indoor temperature when inviting guest (Hitchings, R. and Day, R., 2011).

The review by Brager, G. and de Dear, R. (1998) highlights that these behavioural adaptations may be carried out consciously or unconsciously by the occupants. These may be personal, technological or cultural adaptive actions and practices, and may be influenced by the climate,

the socio-economical constraints, other occupants, future task(s), and the physical context, including the level of control a person has over the surrounding environment. In their home, occupants may have control over a large range of options, from moving around to closing windows and turning on the heating system. Research has shown that occupants in naturally ventilated buildings are comfortable over a wider range of temperatures than occupants in mechanically ventilated buildings (de Dear, R., Brager, G. and Cooper, D., 1997). A study by Brager, G., Paliaga, G. and de Dear, R. (2004) and forming part of ASHRAE RP-1161 aimed to investigate how personal control of windows influences occupants thermal comfort. Surveys were carried out in a large office building in San Francisco Bay area during a 2-week period in the warm and cool season. Each subject was allocated to one of the two "*personal control ratings*", which were defined by the availability of personal control over window operation - with rating "*HI*" for direct control, both in private and open plan offices, and rating "*LO*" for indirect or no control. Results show that the "*HI*" group experienced more thermal variability than the "*LO*" group. Moreover, in the summer calculated neutral temperatures in the "*HI*" group were higher (23 °C) than in the "*LO*" group (21.5 °C); so people with direct control of the window accepted higher neutral temperatures. This study shows that thermal preference may not only be based on physiological and physical factors, but also to the degrees of control over the thermal system. Other studies show similar findings with desktop ambient conditioning systems (Bauman, F., Carter, T., Baughman, A. and Arens, E., 1998), and with use of control, spatial variation, temporal variation, clothing and activity level (Baker, N. and Standeven, M., 1995) (de Carli, et al., 2007). Also, a study by Schweiker, M. et al. (2013) shows that participants with no control over the windows, tend to increase the frequency of other adaptive behaviours such as drinking, and to increase their skin temperature. Controls may be defined and categorised as follows (Paciuk, M., 1990) (Skinner, E., 1996):

- Available or objective control, such as the degree and type of physical control available in the home.
- Exercised or experienced control, such as the controls used by the occupants. One system may be available, for example thermostatic-radiator-valve (TRV), but the occupant may not use it.
- Perceived or subjective control, such as the knowledge and performance of a control strategy.

These three types of control have a direct effect on thermal comfort and the satisfaction with the thermal environment. At home, a common fixture in controlling the heating system is

the residential thermostat (Peffer, T. et al., 2011). However, this device presents a number of conceptual and technical barriers (Kempton, W., 1986) (Peffer, T. et al., 2010).

In the current standard predictive model (ISO 7730:2005), the 6 inputs will be affected by behavioural adaptation; for example, clothing insulation level (I_{cl}) might increase if one puts on a jumper, and ambient air temperature (T_a) might decrease when changing room. However, the localised actions are not accounted for, as these might not be part of physiological or physical changes but a psychological adaptation. The study by Baker, N. and Standeven, M. (1994) aimed to identify these adaptive processes and to incorporate the findings into a predictive comfort model. However, the results from observations and questionnaires only gathered information of the use of clothing and activity. Future studies should aim to capture a much wider range of adaptive behaviour, and to quantify them. Moreover, these may be incorporated into an adaptive predictive approach (Yao, R., Li, B. and Liu, J., 2009) or a feedback loop where the previous state of thermal comfort may be revised by current adaptive behaviour to form future states of thermal comfort.

2.3.4 Thermal comfort practices in winter: sociological and ethnographic perspectives

Drawing on recent studies, this research is investigating how people respond to cold thermal discomfort and their management practices. The first part of this chapter reports quantitative, qualitative and mixed method approaches, where the researcher reviewed peoples responses and ways of keeping warm at home during winter. This second part examines how people would characterise those responses, and the ones of people living around them.

The review by Sovacool, B. (2014) emphasised the important of investigating how norms of comfort management vary between people. A recent study by Gram-Hanssen, K. (2010) applied a practice-theory analysis to understand the technologies, habits, knowledge and meanings that make up the variations in residential heat comfort practices in Denmark. In the UK context, people manage heat flows in their home using many skills, including the use of curtains and draught proofing (Royston, S., 2014). These interactions with the building systems and fabric are not aimed at keeping the heat but rather at achieving personalised comfort. Encouraged by public health and energy demand concern, number of qualitative researches including interviews, diary and observation focused on how and why people respond to cold thermal discomfort (Guy, S. et al., 2014). The influencing factors varied greatly. Within the home, the occupant may be engaging with others; comfort may be negotiated (Tweed, C., et al., 2014). The response may also be part of a range of cultural attributes, past experiences and current pressures. Studies have shown that older people may feel obliged to increase the temperature in

certain rooms when having guest(s) (Wright, F., 2004). This response to specific social interaction may differ greatly to the daily practices as reported in the study by Hitchings, R. and Day, R. (2011). Some heat practices may create stigma; having a cold home may be associated with wealth status in this case poverty, or with the social responsibilities of being "*a good parent*" or "*a good host*" (Hards, S., 2013). On the other hand, some heat practices may be socially positive. Linking to the notions of sustainable consumption, one might choose a colder home as a way to pursue a "*moral identity*" and display their ethical positions as a "*green distinction*" (Hards, S., 2013). Part of social norms, cleanliness may also be associated with the chosen temperature level; as some residents may heat their home to dry their clothes and to avoid mould growth on walls and ceilings (Pink, S., 2012) (Shove, E., 2003). Finally recent ethnographic studies have investigated how cosiness and glow are highly valued by older people. To provide comfort, these two notions may be rated as much as the actual sensation of heat (Devine-Wright, P. et al., 2014).

In summary, how one respond to cold thermal discomfort at home is in part an outcome of social and cultural imperatives. These studies of thermal comfort practices revealed underlying reasons that may not have been looked at when using standard thermal assessment framework. They also demonstrate how qualitative and mixed-methods approaches add valuable insights to thermal comfort research.

2.3.5 Summary

The responses types to thermal discomfort varies greatly. To date, little research has been carried out into the frequency of each response type. There is a need for a new method to monitor thermal discomfort responses objectively. Building on the review of literature, this method may employed a mixed-method approach.

2.4 Human thermal comfort models

Standard thermal comfort models are representations of physical, physiological and psychological systems, and have resulted in a great number of thermal comfort indices (Auliciems, A. and Szokolay, S., 2007) (Carlucci, S. and Pagliano, L., 2012). Only two types of models are included in the current standard. The first type of models, called *predictive*, are built on the principles set by heat balance in the human body. The second type of models, called *adaptive*, are based on field study results. These two types of models are based on empirical studies set in controlled environment or non-domestic settings; thus their applicability to dwellings may be questioned as people have more opportunities to adapt. Field studies have shown that people may employed localised behaviour, and be satisfied with conditions outside the bound of the

models' recommendations (Tweed, C., et al., 2014). This chapter will first describe the existing standards, and then review the principles behind the most common models used to define and assess indoor thermal conditions.

2.4.1 Thermal comfort standards

The current standards focus on the determination of the thermal comfort indices and the specification of the conditions for thermal comfort (Parsons, K., 2003).

The ISO standards on "*ergonomics of the thermal environment*" are used in a complementary way. The main document is ISO 7730, which provides an analytical method to determine and interpret thermal comfort. This method is based upon the predictive model. Other supporting standards include ISO 13731 (vocabulary and symbols), ISO 8996 (determination of metabolic rate), ISO 9920 (estimation of clothing insulation level), ISO 7726 (measuring instruments), and ISO 10551 (subjective assessment). With regards to cold environments, ISO 13732 part 3 focuses on assessment methods of human responses to contact with cold surfaces, ISO 12894 reviews the medical supervision of individuals exposed to extreme hot or cold environments, and ISO 11079 looks at the determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects.

In Europe and the U.K., BS EN 15251 reviews the "*indoor environmental input parameters for design and assessment of energy performance of buildings*", and includes thermal environment. This standard is based on the predictive and the adaptive models.

In the U.S., ASHRAE 55 specifies "*the combination of indoor thermal factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within a space.*" Similar to BS EN 15251, it is based on the predictive and the adaptive models, and also provides recommendations for the assessment of local thermal discomfort.

2.4.2 Predictive approach

As described in the thermal adaptive theory, it is assumed that in free-running buildings, people adapt to the conditions they experience, also comfort temperature will follow changes in outside temperature. However, in heated buildings, the comfort temperature is de-coupled from external conditions, and another set of models are then used to predict occupant thermal comfort levels. In such an environment, thermal comfort is explained by applying physics and physiology to the heat balance of the human environment system, calibrated under controlled laboratory conditions. The heat balance approach is based on two assumptions:

- The combination of skin temperature and core temperature give sensation of thermal comfort.
- The heat produced by metabolism should be equal to the heat lost by the body.

The most notable models are: Fanger model (one-node) (Fanger, P., 1970), Pierce model (two-nodes) (Gagge, A. et al., 1986), and Kansas State University model (two-nodes) (Azer, N. Hsu, S., 1977). These differ in the physiological models employed and the criteria used to predict thermal sensation. Described in ASHRAE 55:2013, EN15251:2007, and ISO 7730:2005, these models are applied to mechanically conditioned buildings (heated and cooled), which aim to provide a uniform environment.

2.4.2.1 Predictive model: Fanger single-node model, ISO 7730:2005

This single-node comfort model is based on the heat balance of the human body. Fanger, P. (1970) proposes that thermal comfort is achieved if the heat flowing to and from the human body is balanced out, this could be summarised in the following equations:

$$H = L \quad (2.1)$$

Where: H is the internal heat production rate per unit area (W/m^2). L represents all modes of energy loss from body (W/m^2).

In this model, the human body exchanges energy with the environment through:

- Evaporation of sweat and/or water vapour diffusion through the skin.
- Respiration.
- Skin exchanges energy by convection and radiation.

These heat exchanges are represented in the following equation:

$$M = E_{sk} + Q_{res} + Q_{dry} + W \quad (2.2)$$

Where: M is the metabolic rate per unit area (W/m^2). E_{sk} is the total evaporative heat loss from skin (W/m^2). Q_{res} is the rate of respiratory heat loss (W/m^2). Q_{dry} is the sensible heat flow from skin (W/m^2). W is the rate of heat loss due to the performance of work (W/m^2); in steady state conditions W is equal to 0 (CIBSE Guide A, section 1.3.2).

The first term, evaporative heat loss from skin (E_{sk}) is defined as:

$$E_{sk} = E_{rsw} + E_{diff} \quad (2.3)$$

Where: E_{rsw} is the rate of heat loss from the evaporation of regulatory sweating at the state of comfort (W/m^2). E_{diff} is the rate of heat loss from the diffusion of water vapour through the skin (W/m^2).

The second term, rate of respiratory heat loss (Q_{res}) is defined as:

$$Q_{res} = E_{res} + C_{res} \quad (2.4)$$

Where: E_{res} is the rate of latent respiratory heat loss (W/m^2). C_{res} is the rate of dry respiratory heat loss (W/m^2).

The third term sensible heat flow from skin (Q_{dry}) is defined as:

$$Q_{dry} = Q_c + Q_r \quad (2.5)$$

Where: Q_c is the rate of convective heat loss (W/m^2). Q_r is the rate of radiative heat loss (W/m^2).

These flows depend on six variables which vary over time:

- Two personal variables: clothing insulation level (I_{cl}) as described in ISO 9920:2009, and activity level (M) as described in ISO 8996:2004.
- Four environmental variables as described in ISO 7726:2001, with (T_a) air dry-bulb temperature, (T_r) mean radiant temperature, (V_a) relative air velocity, and (RH) relative humidity.

As a measure of thermal comfort, the indices of this single-node model predict the mean comfort vote of a group of people, defined as the Predicted Mean Vote (PMV), where:

$$PMV = (0.028 + 0.303 \times e^{-0.036M}) \times (H - L) \quad (2.6)$$

PMV is often translated into Predicted Percentage Dissatisfied (PPD), which is a measure used for benchmarks. PPD is established as a function of the PMV, where:

$$PPD = 100 - 95 \times e^{-(0.03353 \times PMV^4 + 0.2179 \times PMV^2)} \quad (2.7)$$

A seven-point thermal comfort scale is used to describe PMV, ranging from (-3) cold to (+3) hot.

Table 2.1: Seven-point thermal sensation scale. ISO 7730:2005 (Table 1)

Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
-3	-2	-1	0	+1	+2	+3

The recommended categories for design of mechanical heated and cooled buildings are as follows (ISO 7730:2005, Annex A):

Cat. A	$PPD < 6\%$	$-0.2 < PMV < +0.2$
Cat. B	$PPD < 10\%$	$-0.5 < PMV < +0.5$
Cat. C	$PPD < 15\%$	$-0.7 < PMV < +0.7$

Generally, predictive models should be used to assess the occupants level of thermal comfort when a building is mechanically heated, or cooled. It has been recognised that the single-node model is a good indicator but holds formulation and evaluation errors (Humphreys, M. and Nicol, F., 2000). First, the model only takes into account four environmental parameters, and does not account for adaptive opportunities, or habits. Moreover, it has been shown that the model overestimates the thermal sensation response, with a mean error of 1.29 units. Also, the accuracy of this model decreases as metabolic rate and effective temperature increase (Doherty, T. and Arens, E., 1988). The global sensitivity analysis carried out in the following chapter may provide further insights on this last point.

2.4.2.2 Predictive model: Pierce two-node model

The most recent version of the Pierce two-node model was published by Gagge, A. et al. (1986). The human body is modelled as three sections: (1) the core, (2) the skin, and (3) the environment. The heat loss from the skin surface is itself divided into two parts: (2a) the sensible part - including: conduction through clothing, radiation, and convection from the body surface, and (2b) the insensible part - including: evaporation of perspiration on the skin surface. The heat flows between the three main elements are determined on a minute by minute basis, where the initial state is set at T equal to 0 minute, then the model iterates until reaching equilibrium. This should occur within one hour. The two-nodes allow the model to account for heat conduction from the core to the skin. The heat balance equation reads as:

$$M = E_{sk} + Q_{res} + Q_{dry} + Q_{crsk} + W \quad (2.8)$$

Where: M , E_{sk} , Q_{res} , Q_{dry} , and W as per Equation 2.2; and Q_{crsk} is the heat flow from core to skin (W/m^2).

This two-node model has six indices. The first one ET^* , stands for New Effective Temperature, this index accounts for the radiative and latent heat transfers. Using ET^* , the second index $PMVET^*$ is determined by the following equation:

$$PMVET^* = (0.028 + 0.303 \times e^{-0.036M}) \times (H - L_{ET^*}) \quad (2.9)$$

The third index, Standard Effective Temperature, SET relates to the conditions that would give the same physiological response in people with clothing level set at 0.5 clo, metabolic rate set at 1 met, and relative humidity set at 50%. Using SET , the fourth index $PMVSET$ is determined by the following equation:

$$PMVSET = (0.028 + 0.303 \times e^{-0.036M}) \times (H - L_{SET}) \quad (2.10)$$

The fifth index, the Thermal Sensation Index ($TSENS$) is defined in terms of mean body temperature. $PMVET^*$, $PMVSET$, and $TSENS$ using an 11-point scale, ranging from (-5) intolerably cold, to (+5) intolerably hot (Doherty, T. and Arens, E., 1988). Finally, the Discomfort Index ($DISC$) determines the level of discomfort based on the skin temperature and skin wetness. It also uses an 11-point scale, ranging from (-5) to (+5), where comfortable and pleasant (0), slightly uncomfortable but acceptable (1), uncomfortable and unpleasant (2), very uncomfortable (3), limited tolerance (4), and intolerable (5).

Similar to the single-node approach, this model was calibrated in a climate chamber, and in steady state conditions. This might be one of the reasons for its evaluation errors, in particular during exercise simulations (Doherty, T. and Arens, E., 1988). This model was part of the past editions of ASHRAE 55, but recent editions have used PMV. However, building simulation software such as EnergyPlus have included the six indices of the two-node model in its output.

2.4.2.3 Summary

The heat balance models and associated indices are tools, which estimate an acceptable comfort criteria range for a given space. Variables in these models can be modified individually through sensitivity analysis, which generates a rapid feedback for optimisation studies of the overall sequence or individual elements. Through this process, potential heating or cooling systems could be compared at the design stage and potential discomfort identified. The predictive models prescribe a constant environment and they are often referred to as static or constancy models.

Although it is a 'spot' calculation and cannot predict the response to a step-change, input may be modified at regular intervals and reflect changes in a person's environment. Specifically reviewing the PMV-model, Humphreys, M. and Nicol, F. (2002) concluded that it was "*free from serious bias*", despite the fact that 16,762 discrepancies were observed between reported thermal perception and calculated PMV. The reported mean discrepancy was 0.11 ± 0.01 PMV unit, which is not large but statistically highly significant. On the other hand, the standard deviation was 1.22 PMV unit, which is considered large, and attributed to individual variables bias and their joint effect.

The predictive models present some limitations as their assumptions are based on deterministic logic, where thermal stimuli are exclusively linked to the heat exchange between the participants body and its environment. However, thermal perception is also influenced by psychological, social and cultural factors (Brager, G. and de Dear, R., 1998).

Moreover, it is assumed that the predictive models may be applied in different locations, seasons, for all types of buildings and occupants (de Dear, R. et al., 2013). The review by van Hoof, J. (2008) shows that the PMV-model does not account for person-to-person differences. Using the ASHRAE database, which consists of over 20,000 individual comfort votes, (Humphreys, M. and Nicol, F., 2002) show a systematic deference in thermal perception between naturally ventilated and air-conditioned spaces. Also, two variables, activity level and thermal resistance of clothing cannot be measured with accuracy (Brager, G. et al., 1993).

To answer to part of these limitations, a study by Fanger, P. and Toftum, J. (2002) proposes an extension to the PMV model to non-air-conditioned buildings in warm climates. This new model includes an expectancy factor (e) to be multiplied with PMV, varying between 1 and 0.5 depending on the frequency of warm periods and the most common ventilation strategy in the region. Another study by Yao, R., Li, B. and Liu, J. (2009) proposes an Adaptive Predictive Mean Vote model (aPMV), which includes an adaptive coefficient (λ), function of physical stimuli, and psychological and behavioural impact coefficient. (λ) is defined as the difference between indoor resultant air temperature and thermal neutral temperature. In cold conditions, aPMV will be lower than PMV and the opposite in warm conditions. This new model allows for the application of the PMV model in naturally ventilated buildings, and takes into account local climate, and personal characteristics.

Finally, the predictive models, associated inputs and indices were developed by engineers and physicists, and answered a need from the building industry to specify and evaluate HVAC systems (Nicol, F., Humphreys, M. and Roaf, S., 2012). As questioned in the study by Tweed, C., et al. (2014), this predictive approach may not be relevant to domestic settings as conditions

may vary greatly throughout the day, and occupants have greater opportunities to adapt.

2.4.3 Predictive model variables

To follow the heat-balance models' principles, human thermal comfort is dependent upon environmental variables (EV), and personal variables (PV). These input variables include air temperature (T_a), mean radiant temperature (T_r), relative humidity (RH), relative air velocity (v_a), clothing insulation, (I_{cl}) and metabolic rate (M).

2.4.3.1 Air temperature (EV1) - ISO 7726:2001

Air temperature (T_a) is defined as the temperature of air surrounding the body. It is given in degree Celsius ($^{\circ}\text{C}$), in degree Kelvin (K) or degree Fahrenheit ($^{\circ}\text{F}$). As described in ASHRAE 55:2013 and ISO 7730:2005, thermal stratification may cause local thermal discomfort when vertical air temperature difference (ΔT) between a persons feet and head is too great. Olesen et al. (1979) conducted a study in a controlled environment in which 16 subjects were exposed to 4 levels of stratification from 0.4K to 7.5K; it concluded that 5 to 10% of people would feel uncomfortable if the difference was greater than 3 to 4K. The current standards are based on the result of this study, and set the following thresholds:

- ASHRAE 55:2013: $\Delta T < 3^{\circ}\text{C}$ with thermal insulation of clothing set at $0.5 < I_{cl} < 0.7$ and activity level set at $1.0 < M < 1.3$
- ISO 7730:2005: Cat. A: $\Delta T < 2^{\circ}\text{C}$, Cat. B: $\Delta T < 3^{\circ}\text{C}$, and Cat. C: $\Delta T < 4^{\circ}\text{C}$

To date, research on thermal stratification in buildings and its effect on occupants thermal comfort have largely focused on commercial buildings with forced-convection ventilation systems (Schiavon, S. et al., 2014), and there is currently a lack of empirical evidence in residential settings.

2.4.3.2 Mean radiant temperature (EV2) - ISO 7726:2001

Thermal radiation is the heat that radiates from all objects. It is given in degrees Celsius ($^{\circ}\text{C}$), in degrees Kelvin (K) or degrees Fahrenheit ($^{\circ}\text{F}$). Significant radiant heat transfer may be present if there are heat sources in an environment, such a radiator or a fire, or cold sources such as exposed mass or low performance windows. The mean radiant temperature is defined in ISO 7726: 2001 (Annex B) as *"the net amount of the radiant heat lost or received by the human body"*. It may be estimated by the location, dimension, surface temperature and emissivity of the heat source. Radiant heat has great influence on how the human body loses or gains heat to the environment, as the skin absorbs almost as much radiant energy as a matt black object, although this may be reduced by the type of clothing worn. A study by Arens, E. et al. (2014)

aimed to model the comfort effect of short-wave solar radiation indoors, where the effective radiant field is a function of the fraction of the body surface exposed to radiation, the radiation heat transfer coefficient, the air temperature and the mean radiant temperature. Results show that solar radiation may cause discomfort, and require additional cooling capacity in summer while in winter it may drive lower heating demand.

With regards to local discomfort, floor temperature may have an impact. For category C - PPD <15%, floor temperature should be between 17 and 30 °C (ISO 7730:2005) when people are standing and/or sedentary. Another local discomfort effect is the radiant asymmetry that may occur in an indoor environment, for example cold walls or warm ceilings.

2.4.3.3 Relative humidity (EV3) - ISO 7726:2001

Absolute humidity is the amount of water in a given volume (or mass) of air as the moisture content of air - unit can be expressed in either (g/m^3), (g/kg), or (Pa). Relative humidity is related to the moisture content of the air and the dry bulb temperature. It is expressed as the percentage of, or ratio between [the partial vapour pressure of water] and [the saturation vapour pressure at that temperature], and is expressed in percentage (%). As per CIBSE Guide A, the acceptable range is 40 to 70%, although lower humidity up to 30% is acceptable for short periods of time. Ballantyne, E., Hill, R. and Spencer, J. (1977) have found that humidity has an effect on perceived thermal comfort; as vapour pressure increases, the temperature at which thermal sensation is reported as comfortable decreases, for example the lower range of 'comfortable' is at 23.9 °C at 0-1 kPa, and decrease to 23.1 °C at 2-3 kPa. This effect becomes larger as thermal sensation increases, where the lower range of 'hot' is at 38.6 °C at 0-1 kPa, and decrease to 34.2 °C at 2-3 kPa. As humidity gets higher, the bodys evaporative heat loss is impaired and, therefore, comfort temperatures are lower. The study by Nicol, F. (2004) concluded that when *"humidity is high people may require temperatures that are about 1 °C lower to remain comfortable, but the main effect of a higher humidity (or water vapour pressure) is to reduce the width of the comfort zone"*.

2.4.3.4 Relative air velocity (EV4) - ISO 7726:2001

Relative air velocity (v_a) is defined as the speed of air moving across an occupant, and is given in meters per second (m/s). It is characterised by the direction of the air flow, and by the velocity fluctuations (ISO 7726:2001, Annex E).

Moving air increases the bodys heat loss through convection without any change in mean air temperature. If the air temperature is lower than skin temperature, it will significantly increase convective heat loss of the body. In particular, physical activity increases air movement around the body, so air velocity may be corrected in thermal comfort models to account for a

person's level of physical activity (Jones, B., Hsieh, K. and Hashinaga, M., 1986).

Air movement in an indoor environment will increase convection within the space, and instigate larger vertical air temperature difference, which may cause local discomfort (ISO 7730:2005). Also, air movement in cool or cold environments may be perceived as a draught. Draughts are a function of local air temperature, local mean air velocity and local turbulence intensity (ISO 7730:2005). In warm conditions, increased air movement can increase indoor comfort temperature up to 3.5 °C for example, the use of a fan generating an air velocity of 0.45 m/s will allow an increase in an indoor set point of 2 °C (Nicol, F., 2004).

2.4.3.5 Metabolic rate (PV1) - ISO 8996:2004

Arisen from laboratory experiments in climate chambers, the current standards combine knowledge of the human body physiology and of heat transfer theories. They form part of the International Standard Organisation in BS EN ISO 7730:2005, and BS EN ISO 8996:2004. The work or metabolic rate is described as the heat produced by the human body to carry out physical activity. The more physical work is carried out, the more heat is produced, and the higher the metabolic rate. A person's physical activity is characterised by its type, intensity, duration, and frequency (Chen, K. and Bassett, D., 2005). When metabolic rate is high, the human body needs to lose heat to prevent overheating.

In the standards, methods have been developed to estimate activity level and to analyse the relationship between activity level and thermal comfort. As described in ISO 8996:2004, metabolic rate (M) is a measure of activity level and is defined as the rate, at which the human body utilises oxygen, food, and other sources to produce energy, per surface area of the body. In summary, it refers to the rate of production of energy in time per surface area, and is expressed in watts per squared meter (W/m^2), or in metabolic unit (met), where 1 met is equal to 58.2 W/m^2 . Based on this definition, a person's metabolic rate consists of two components:

- Body surface area (BSA), which is assumed to be 1.8m² for a man of 70kg, and 1.6m² for a woman of 60kg (Parsons, K., 2001).
- Energy expenditure (EE), which refers to the energy used per unit of time to produce power, and is expressed in watts (W) or more often in mega-joules per day (MJ/day) (Jeukendrup, A. and Gleeson, M., 2004).

Metabolic rate (M) can estimated by using the following equation:

$$M = EE \div BSA \quad (2.11)$$

Where: M : metabolic rate (W/m^2); EE : energy expenditure; BSA : body surface area.

Methods to estimate or to measure human energy expenditure range from direct to indirect methods with associated level of complexity and cost. ISO 8996:2004 provides the methodological framework to estimate this metabolic rate. It includes four levels, screening (1), observation (2), analysis (3) and expertise (4). When assessing metabolic rate, it is essential to consider a persons physical and physiological characteristics such as gender, age and weight. These can have an impact on how comfortable occupants felt, even if environmental factors are constant.

2.4.3.6 Clothing insulation (PV2) - ISO 9920:2007

Clothing insulates the body, and interferes with our ability to lose heat to the environment, therefore thermal comfort is very much dependent on the insulating effect of clothing worn. The standard value 'clo' is a measure of the thermal resistance of a garment itself, and also includes the insulation of trapped air between the skin and the item of clothing; 1 clo is equal to $0.155 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$, or to 1.55 tog (ISO 9920:2007). Clothing increases the surface area of the body, forms a resistance to the release of water vapour from the skin, and decreases heat loss. The level of these effects is dependent on the size and quality of the garment, as well as its thickness and porosity.

Wearing too little clothing may cause hypothermia if the environment is considered cool or cold. Clothing is both a potential cause of thermal discomfort as well as a control strategy. An occupant may choose to add layers of clothing if feeling cold, or remove them if warm (Baker, N. and Standeven, M., 1997) (Morgan, C. and de Dear, R., 2003) (de Carli, et al., 2007). The level of clothing insulation may be reduced by the increase of ambient temperature, of air velocity, and/or of activity level. To determine clothing insulation one or a combination of the following methods may be used:

- Estimation from typical ensembles or from individual garments (ISO 9920:2007).
- Adjustment when sited on a chair, or for moving occupants (ASHRAE 55:2013).
- Estimation as a function of outdoor air temperature at 6am (ASHRAE 55:2013).

However in most cases, the clothing insulation is given a constant value equal to 0.5 clo in summer and 1 clo in winter (Schiavon, S. and Lee, K. H., 2013).

2.4.4 Adaptive approach

Adaptive models are derived from statistical analysis of empirical study results, and assume that occupants preferred indoor temperature varies with external weather conditions (Nicol, F. and Humphreys, 2004). Unlike the heat-balance method, it does not require knowledge of clothing or activity level of occupants. Therefore, people's behaviour may vary according to the different seasons; summer, autumn, winter, and spring. Field studies suggest that in free-living environments people are more tolerant of temperature level and change than in laboratory studies. Intended for naturally ventilated buildings, the adaptive models are part of the ASHRAE 55:2013 and the EN15251:2007. Adoption of adaptive approach can lead to energy saving, and less strict controlled environments, as occupants are given time and opportunity to adapt through different strategies. As the air temperature changes, so the level of activity, clothing, and air movement may change too.

2.4.4.1 Adaptive model: ASHRAE 55:2010

As thermal adaptation is by nature a dynamic process, an occupant may be accustomed to a range of comfortable indoor temperatures that will change in time and through different spaces within a dwelling. Early studies reported that the indoor temperature was associated with outdoor temperature, and that this relationship was linear (Humphreys, M., 1978). In the ASHRAE 55:2013 this relationship is stated as:

$$T_{ot} = 0.31 \times (T_o + 17.8) \quad (2.12)$$

Where: T_{ot} is the operative temperature ($^{\circ}\text{C}$). T_o is the running mean outdoor air dry-bulb temperature over the previous thirty days ($^{\circ}\text{C}$).

For the assessment of buildings, the limits of the comfort zones are given by the following two categories:

$$\begin{aligned} \text{Cat. I} \quad & 90\% \text{ acceptability} \quad T_{ot} = 0.31 \times (T_o + 17.8) \pm 2.5 \\ \text{Cat. II} \quad & 80\% \text{ acceptability} \quad T_{ot} = 0.31 \times (T_o + 17.8) \pm 3.8 \end{aligned}$$

This model is only applicable for the following conditions:

- Naturally ventilated buildings.
- Occupants engaged in near sedentary physical activities (1 to 1.3met).
- T_o ranging from 10°C to 33.5°C .

Also, it is essential that the occupants have the opportunity to adapt by adjusting their clothing, opening/closing windows, or by other means.

2.4.4.2 Adaptive model: EN 15251:2007

In Europe, extensive surveys in offices were conducted, and equations for optimum comfort were developed from the SCATs project (McCartney, K. and Nicol, F., 2002), giving:

$$T_{ot} = 0.33 \times (T_o + 18.8) \quad (2.13)$$

Where: T_{ot} is the operative temperature (°C). T_o is the running mean outdoor air dry-bulb temperature over the previous seven days (°C).

Limits of the comfort zones are given by the following three categories:

Cat. I	90% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 2$
Cat. II	80% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 3$
Cat. III	65% acceptability	$T_{ot} = 0.33 \times (T_o + 18.8) \pm 4$

This model is only applicable for the following conditions:

- Free-running buildings with operable windows and clothing adaptation.
- Occupants engaged in near sedentary physical activities (1 to 1.3met).
- T_o upper-marging, from 10°C to 30°C.
- T_o lower-marging, from 15°C to 30°C.

For example, in the UK, the running outdoor mean temperature over thirty days in winter is likely to be below the degree day, set at 15.5°C (Chartered Institution of Building Services Engineers (CIBSE), 2006). As the adaptive model can only be applied for T_o higher than 15°C, the assessment of buildings in winter may use the predictive approach.

2.4.4.3 Summary

As occupants adapted to their environment, studies show that preferred indoor temperature increases in warm conditions, and decreases in cold conditions (van Hoof, J., Mazej, M. and Hensen, J., 2010). Using meteorological records, a linear relationship between preferred indoor temperature and outdoor temperature is used to predict the likely comfort temperature in free-running buildings. Passive design which use little energy to temper the building can be assessed with this relationship.

The review by Halawaa, E. and van Hoof, J. (2012) highlights some of the limitations of the adaptive model, including the following:

- The only dependent variable is running mean outdoor air temperature; the approach does not address directly the localised variables, such as relative air velocity, the level of clothing or activity. To date, there is a lack of evidence in investigating the relationship between outdoor temperature and the six predictive factors, in particular relative air velocity, radiant temperature and activity level.
- Although the ASHRAE 55:2013 and the EN 15251:2007 are based on the same concepts, there are several differences, including: the building types, the weighting factors, the definition of mean outdoor temperature, and the applicable range of mean outdoor temperature.
- There is little evidence that "*cultural and social contextual dimensions*" have been taken into account in the model.

Drawing on this last point, studies have shown how social and cultural aspects may influence people's practices to manage cold at home (Shove, E., 2003) (Hitchings, R. and Day, R., 2011). Although the adaptive approach stresses the importance of contextual factors, the model only account for external temperature as an independent variable. This gap calls on a new method to monitor people thermal discomfort responses to be developed. Furthermore, this research is set in domestic environment where there is little evidence of actual warmth practices, as most studies have focused on reported accounts (Hinton, E., 2010). Self-reported evidences have enabled warmth practices to be recorded, and an "*inventory*" to be drawn. However interview and survey have limitations as reviewed in Chapter 5, in particular the interviewer effect. Therefore, these methods may be complemented by others such as monitoring and automated diaries, which record participants actual responses. These methods also hold bias such as the Hawthorne effect. In conclusion, this research question calls for a mixed-method approaches to cross-validate results.

2.4.5 Application of thermal comfort models

As highlighted in the introduction, there has been a drive in recent years to reduce energy used in buildings while minimising impacts on occupants thermal comfort. To address this issue, building design tools and assessment frameworks have included thermal comfort indices in the analysis process as design targets or boundary conditions. This chapter will review the application of thermal comfort models in the design, assessment and operation of buildings.

2.4.5.1 Psychometric charts

A psychrometric chart is a graph including environmental parameters set as dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, humidity ratio, and specific enthalpy (Auliciems, A. and Szokolay, S., 2007). At the early building design stage, psychrometric charts may be used to assess the potential Passive Environment Strategies (PES) a site may offer. These PES may enable the reduction in space heating demand. As an example, UCLAs Energy Design Tools, Climate Consultant version 5.4 was used to determine how effective PES can be to maintain indoor thermal comfort conditions in London. On the psychrometric chart, each day is represented as a 'green-dot', and the effect of PES at maintaining thermal comfort conditions is represented as a superimposed polygon. The more effective the PES, the more days are included in the polygon. All year round, the passive strategies which have some effect are (see Figure 2.4):

- Sun shading and passive solar heating (2), (10) and (11) - representing 16% of comfortable hours;
- Thermal mass effect (3) and (4) - representing 0.6% of comfortable hours;
- Evaporative cooling (5) and (6) - representing 0.6% of comfortable hours;
- Natural ventilation (7) - representing 4.7% of comfortable hours;
- Wind protection (12) - representing 1.1% of comfortable hours.

In winter and mid-season (October to March), the passive strategies which have some effect are (see Figure 2.5):

- Passive solar heating (10) and (11) - representing 4.8% of comfortable hours;
- Wind protection (12) - representing 1.7% of comfortable hours.

Figure 2.4 shows which passive strategies increase the occupancy hours in the thermal comfort zone, and which are efficient environmental strategies. Specifically, for winter and

mid-seasons, Figure 2.5 shows that to improve indoor thermal comfort, designs should include passive solar heating, and wind protection. However, these passive measures will only be effective for 6.5% during winter and mid-seasons, therefore passive design has its limits. For the remaining time, some form of heating will be required according to the standard comfort models. In summary, at the early design stage, psychrometric charts are a useful tool to assess a site, however, it only gives broad insights based on a large number of assumptions (i.e. neighbourhood and building morphology, building fabric and occupancy).

Furthermore ASHRAE 55:2013 includes psychrometric charts in the graphic comfort method (5.3.1). For relative humidity levels ranging from 20 to 80%, the operative temperature shall be between: the lower band of [19.5 to 21.5 °C] and the higher band of [27 to 28.5 °C]. This method is limited to metabolic rate between 1.0 and 1.3met; clothing insulation between 0.5 and 1.0 clo; and air velocity lower than 0.2 m/s. Although this method may be useful at the early design stage, the limitations are rather restrictive, and the operative temperature range narrow (Halawaa, E. and van Hoof, J., 2012). Therefore, it is suggested to use the analytical comfort zone method at a later design stage.

Figure 2.4: Psychrometric chart of London Gatwick for the whole year, and associated environmental strategies

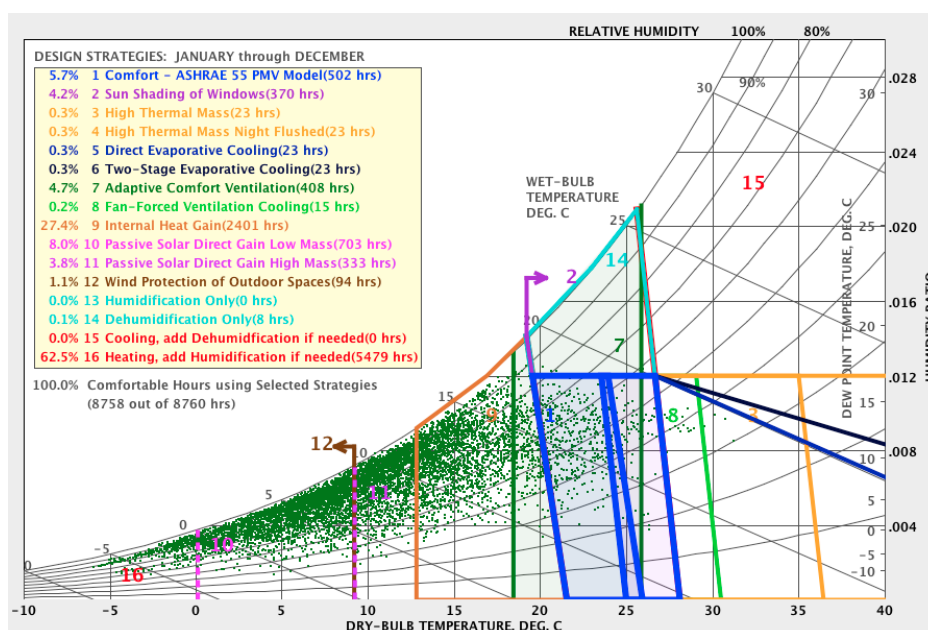
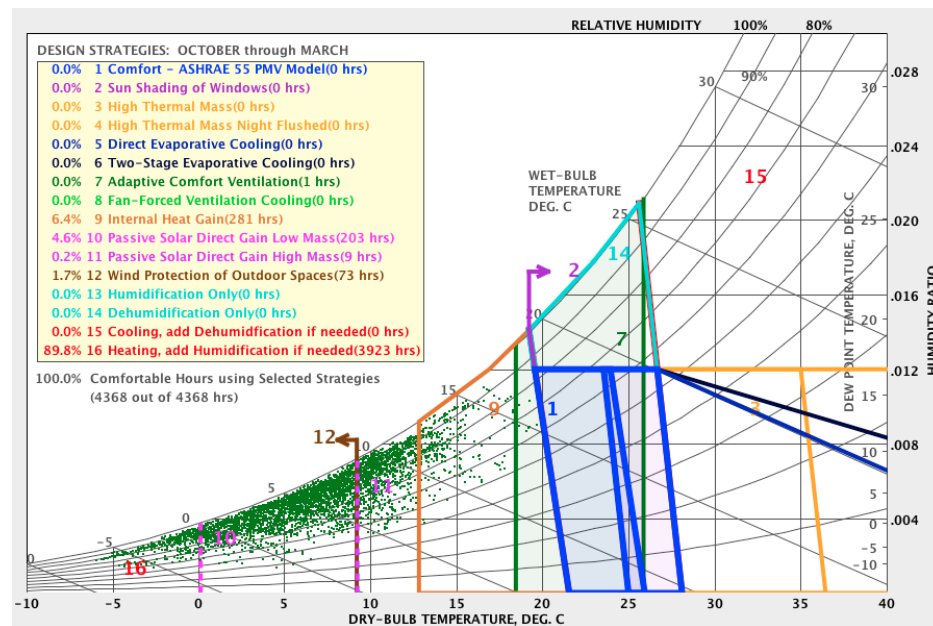


Figure 2.5: Psychrometric chart of London Gatwick for winter and mid-season, and associated environmental strategies



Note: Software used UCLAs Energy Design Tools, Climate Consultant version 5.4, which can be downloaded from, www.energy-design-tools.aud.ucla.edu. EnergyPlus website contains the climate data, the file used is London Gatwick 037760 (IWECC).

2.4.5.2 Building energy simulation

Most existing building energy simulation (BES) programs aim to solve conditions of a volume, given a set of inputs and outputs, and using volume control analysis (i.e. TAS, EIS, EnergyPlus software). The intent is often to minimise energy demand while keeping occupants comfortable. With regards to thermal comfort, hygrothermal set-points and/or comfort indices levels are assigned as boundary conditions to the models. The fundamental structure of this type of software limits the level of analysis, as localised discomfort can only be studied by setting multiple volumes within one room.

One of the limitations of BES simulation is the requirement for balanced airflow within one zone. For naturally ventilated buildings, this may not be the case. Moreover, BES models assume that air temperature is the same within a given volume. However, thermal diversity in a building is one of the solutions put forward in the quest to reduce energy demand. Therefore, it may be interesting to use heuristic methods or monitored stratification profiles as inputs to future BES models.

2.4.5.3 Computational fluid dynamics models and coupling methods

Building energy simulation programs often use standard thermal comfort indices and thresholds. However, most of them focus on comfortable indoor hygrothermal levels, rather than spatial distributions and localised discomfort. To investigate thermal stratification in a room, discrete analysis should be used. This method solves a grid of points within a volume using the principles of fluid dynamics (i.e. OpenFOAM software). As an analysis method, Computational Fluid Dynamics (CFD) may be used to provide a detailed analysis of the thermal environment within a room.

Webb, A. (2012) (?) developed a software, cMap, written in Python and using input data files from EnergyPlus for the room geometry, thermal properties and external weather conditions. After selecting the thermal comfort index and timeframe output, cMap produces contour heat-map as 2D slices through the space in any direction and at any location. One of the drawbacks of this software is that the EnergyPlus input assumes that air temperature (T_a), relative air velocity (v_a), relative humidity (RH), metabolic rate (M) and clothing insulation, (I_{cl}) are constant across a room. Only mean radiant temperature (T_r) and the comfort indices are discrete outputs. However, the coupling of BES and CFD allows the analysis of stratification in heights and levels with realistic boundary conditions from the BES input (Mirsadeghi, M., Blocken, B. and Hensen, J., 2008). Another coupling method, DesignBuilder CFD software may be used to simulate heat and mass transfers within a room. Prior inputs should be specified including location, orientation, fabric, ventilation and heating system characteristics. These define the geometry and boundary conditions of the models. The EnergyPlus model can then be set to run for hourly intervals during the required period, and using the appropriate weather file. CFD boundary conditions can then be extracted from the BES model. DesignBuilder CFD generates automatically a uniform rectilinear Cartesian grid with a default spacing of 0.3m and merging tolerance of 0.03m. The chosen CFD grid should have an acceptable ratio for modelling a room (Baharvand, M. et al., 2013). The simulation may use different equation, turbulence model and discretisation scheme with the aim to result in a converged solution with optimal number of iterations.

Furthermore, CFD results may be fed back to the BES model. The resultant output will be an estimation of temperature at different heights within the studied volume; this could then be taken as an input to predict thermal comfort level. In turn, this may lead to a new technique to infer predicted thermal comfort levels due to stratification effect in a room. In conclusion, the coupling method has the potential for building-in greater thermal variability into existing simulation tools and making thermal comfort analysis more robust.

2.4.5.4 Assessing buildings

A number of assessment systems have been introduced around the world including BREEAM and the Code for Sustainable Homes in the UK, and LEED in the US (Saunders, T., 2008). Launched in 1990, BREEAM is used to assess existing buildings and new developments from 'conception' to 'in-use'. Thermal comfort assessment is part of 'Health and Wellbeing' indicators, it aims to ensure appropriate thermal comfort levels and specification of control systems. The benchmark criteria are set by CIBSE Guide A (Chartered Institution of Building Services Engineers (CIBSE), 2007). For LEED assessments, thermal comfort is part of the 'Indoor Environmental Quality' credit category, and requires HVAC systems to meet the requirement of ASHRAE 55. Both assessment systems' benchmark criteria may be difficult to meet for naturally ventilated or mixed mode buildings, however alternative compliance path such as bespoke assessment may be granted.

Once the building is in-use, the post occupancy evaluation (POE) may be carried out to assess how well the building matches the users' requirements and expectation for performance, health, safety and comfort (Leaman, A. and Bordass, B., 2007) (Deuble, M. and de Dear, R., 2012). Results of these surveys are then used to identify ways to improve building design and performance. POE often use mixed-methods assessments including social survey and environmental monitoring. In particular, the Building Use Studies (BUS) methodology may be used to collect occupant feedback on their perceived comfort conditions (Usable Buildings Trust, 2012). The survey consists of 46 questions with a 7-point scale. With regards to thermal comfort assessment, eight questions are particularly relevant, and include occupants perceptions of typical conditions for winter and summer indoor temperature and air quality, and overall comfort satisfaction. The questions on winter and summer temperature include the following scales (1) 'uncomfortable' to 'comfortable', (2) 'too hot' to 'too cold', and (3) 'stable' to 'varies during day'. POE using surveys such as BUS allows for a rapid assessment of occupant comfort level and comparison to benchmark references. However, there is a limit to the conclusions drawn from the results of such a survey, as it is only a 'snapshot' and not a longitudinal survey. Also it relies on occupants' memories, and occupants may be motivated to respond in a certain way.

2.4.5.5 Building management and operation

With the recent advancement of computer sciences, buildings can now be managed using real-time measurement and network technologies (Tse, W. and Chan, W., 2007) (Kumar, A., Singh, I. and Sud, S., 2010) (Revel, G., Sabbatini, E. and Arnesano, M., 2012). Smart sensors may be employed to monitor environmental parameters, occupancy pattern and energy use. The data collected may be transferred through the network, and then analysed to control the building

systems, including heating and cooling. The analysis may use the current thermal comfort models and benchmarks in the control system algorithm; for example **"if** people in the room **and** $PMV \leq 0.7$ **then** turn on heating". This comfort control network may become an essential element in building energy demand management, however the question of control may be raised - can the occupants override the system? This is particularly important management of energy demand (Warren, P., 2014).

2.4.5.6 Summary

This section carried out a review of the application of thermal comfort model, indices and benchmarks throughout the building design, construction and occupation.

2.4.6 Summary

The review by Carlucci, S. and Pagliano, L. (2012) proposes a framework to classify the different families of indices for the long-term evaluation of general comfort conditions in buildings. Some indices are based on comfort models, other on reference temperatures; within each of these two categories, indices may be defined as a percentage, cumulative, risk, and averaging. In particular, comfort evaluation may be based on the percentage of time outside the PMV range (predictive approach) or the degree-hour criterion (adaptive approach). The adaptive and predictive models form the basis to the current standards that prescribe acceptable conditions for thermal comfort. Although both model-types have been validated to some extent, their accuracy is highly dependent on the models' input, and the models' assumptions. Currently, these models are applied across all building types and population, this may be questioned as thermal perception may be influenced by different settings, social and personal characteristics (Parsons, K., 2003).

2.5 Measurement and assessment methods

This chapter will review first the current approaches, method and techniques to collect and to analyse thermal comfort assessment; then a review of the key studies undertaken to date will be carried out.

2.5.1 Thermal comfort assessment

Thermal comfort assessment in dwellings often involve surveys, modelling and analysis (Osland, N., 1994) (Crosbie, T., 2006) (Hong, S. et al., 2009). Usually, these studies use mixed methods approaches, which include standard comfort questionnaires, and monitoring of environmental parameters. The samples are often characterised by building technical characteristics (i.e. type, size and age), by household energy usage, and by socio-demographic characteristics (i.e. household composition, income, ownership, etc.). These studies investigate relationships between social or technical factors, and participants thermal comfort level or indoor temperatures. Surprisingly, occupants actual responses to thermal discomfort are not investigated. Even though important technical aspects are revealed, practices and behaviour responses towards thermal discomfort are overlooked. In winter, behavioural adjustments, such as increased clothing and metabolic rate may shift thermal neutrality and undermine the assessment results. The research approach for developing a method to map people thermal discomfort is twofold:

- To identify the key parameters to be addressed.
- To determine a method to collect and assess each parameter.

Drawing on from the predictive and adaptive approaches, the key parameters could either be Environmental Variables (EV) or Personal Variables (PV). These may be assessed using subjective and objective assessment. They are measured or estimated at the time of the survey or through continuous periods of time. The core set of recordings common to most thermal comfort studies are summarised in Table 5.2. Studies should collect information regarding the 'typical' factors, and may gather additional information to address any specific research questions.

Table 2.2: Key factors to be recorded in thermal comfort studies

	Environmental Variables (EV)	Personal Variables (PV)
Typical	Internal dry-bulb air temperature (T_a) (c, l)	Activity level (ISO 8996, level 1 and 2) (M) (c)
	Internal mean radiant temperature (T_r) (c, l)	Thermal insulation level (observed or self-reported) (I_{cl}) (c)
	Internal relative humidity (RH) (c, l)	Thermal perception (self-reported, ISO 10551) (c)
	Internal mean air velocity (v_a) (c, l)	.
	External hygrothermal conditions	.
	Building location and type	.
Additional	Internal vertical hygrothermal stratification (c, l)	Socio-demographic factors (incl. age, gender, income, education level, etc.) (c)
	Internal variation in air velocity and turbulence intensity (l)	Physiological conditions (incl. heart-rate, skin temperature, core temperature, etc.) (l)
	Building layout (c)	Activity level (ISO 8996, level 3) (M) (l)
	Building fabric (c)	Thermal insulation level (monitoring) (I_{cl}) (l)
	Building systems (c)	Affective assessment and thermal preference (self-reported, ISO 10551) (c)
	.	Air movement preference (c)
	.	Perceived control (c)
	.	Typical reported response to discomfort (incl. change of clothing level, activity, or location, intake of warm drink, etc.) (c)
	.	Occupancy schedule (l)
	.	Observations (incl. automated visual diary) (l)
(c) Cross-sectional study		
(l) Longitudinal study		

Within the applied methods and techniques to map peoples thermal comfort level, there is a lack of consistency (Brager, G. and de Dear, R., 1998). Largely cross-sectional, the studies consist of a questionnaire with associated rating scales while simultaneously recording the six predictive factors. Three classes of field investigation can be discerned in the literature based on standard of instrumentation and procedure (de Dear, R., Brager, G. and Cooper, D., 1997) (Nicol, F., Humphreys, M. and Roaf, S., 2012), defined as follow:

- Class III: one level of measurement of indoor temperature (T_a) and relative humidity (RH) (EV), and "right-now" thermal questionnaire survey (PV).

- Class II: indoor measurements of the four environmental variables (T_a , T_r , RH , and v_a) (EV), collected at the same time and place as the "right-now" thermal questionnaire survey (PV).
- Class I: sensors and procedure compliant with the specification of ASHRAE and ISO, including three heights of measurements (EV), and several surveys of comfort vote enhanced by detailed measurement on clothing and activity levels (PV).

Other information collected may include location, climate and season, description of sample buildings, outdoor meteorological data sources.

2.5.1.1 Subjective assessment

In order to establish how people feel thermally and how they respond to discomfort, surveys may be conducted. As environments are ever changing, these surveys should be systematic, and enable the monitoring of local conditions and behaviours. Occupant surveys address the following aspects:

- Assessment of thermal perception, affective assessment, thermal preference, personal acceptability, and personal tolerance (ISO 10551:2001).
- Estimation of clothing insulation and activity level as the predictive approach personal variables (ISO 9920:2009, and ISO 8996:2004).
- Subjective assessment of thermal comfort using questionnaires, interviews or focus groups.
- Behaviour observation.

These approaches may be used as 'stand-alone' methods or concurrently to environmental monitoring. The information gathered may be of two types:

- Direct account from the participants - reported information.
- Indirect account from an observer or a sensor - recorded information.

The first factors to be assessed are the occupants' levels of thermal perception, thermal preference, and associated affective assessment (ISO 10551:2001), for example the following question may be asked to the participants:

1. [Thermal Perception] How do you feel at this precise moment?

Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
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2. [Affective Assessment] Do you find this?

Comfort- able	Slightly un- comfortable	Uncomfort- able	Very un- comfortable	Extremely uncomfort- able
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3. [Thermal Preference] At this moment, would you prefer to be?

Much warmer	Warmer	Slightly warmer	Without change	Slightly cooler	Cooler	Much cooler
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A study by Brager, G. et al. (1993) reviewed methods for assessing thermal sensation and acceptability in field studies. In particular, how can an environment be considered thermally acceptable? To answer this question, the threshold of 80% approval rate was set. This translates into four methods including determining the percentage of votes falling within the 3 central categories of the 7-point thermal perception scale. In turn, this pre-supposes that thermal neutrality is the preferred sensation, which might not be the case for all (de Dear, R., 2011). Reviewing the formulation of the assessment scales, the study concluded that categories labelled '*slightly ... warm, cool, uncomfortable, warmer, or colder*' may be included in the definition of acceptability. Results of the study show that this expanded comfort acceptability range is better aligned with the resultant PPD. Moreover, the study concluded that thermal sensation outside of the three central categories may not infer discomfort for some participants. Also, thermal discomfort vary asymmetrically around neural sensation.

Another study, which was carried out as part of the SCATs project, used a questionnaire survey to collect subjective thermal comfort data (McCartney, K. and Nicol, F., 2002). In particular, it included the 7-point thermal perception, and the 5-point thermal preference scale. It also assessed other environmental parameters, including the perception of the air movement, humidity, light level, background noise, air quality, as well as their activity and clothing levels, and finally occupants' perceived control over their environment. Some of questions were also included in the study by de Dear, R., Brager, G. and Cooper, D. (1997) (Appendix E). To draw

on from these examples, these research questionnaires and interviews may include the following questions:

4. [Air Movement] At this moment, how is the air movement around you?

(6) Very					(1) Very
Acceptable	(5)	(4)	(3)	(2)	Unacceptable

5. [Air Movement] Taking into account your personal preference only, would you change the air movement?

More	No Change	Less
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6. [Activity Level] Looking at this card, how would you describe your activity level in the last 10 minutes?

7. [Activity Level] Looking at this card, how would you describe your activity level between 10 and 30 minutes ago?

8. [Thermal Insulation Level] Looking at this card, how would you describe your clothing?

9. [Perceived control] How do you perceive the control over your thermal environment?

(1) No				(5) Complete
Control	(2)	(3)	(4)	Control

With regards to the format of the questions, it may be associated with answer-choices such as the framework of the ISO 10551:2001 (Annex B), or allows for a continuous scale by using a slider, as suggested in EN 15251:2007 (Annex H). Both standard formats are close-ended and ordered, aiming to complete a subjective evaluation by quantifying a theme. These questions may be used in surveys conducted "face-to-face" between a participants and an interviewer, or over the phone (Tweed, C., et al., 2014). They may also be used in postal and electronic surveys.

In contrast, to map people's thermal discomfort responses at home, one might use open-ended questions in interviews. This method was used in a study by Burris, A., Mitchell, V. and Haines, V. (2012) to gain an understanding of how occupants create comfort at home, and in another study by Henning, A. (2006) to assess the value of qualitative methods in supporting the development of more flexible and energy saving thermal comfort. In both studies, a rich account of occupants' experiences was uncovered, in particular thermal comfort was linked to 'keeping warm' by adjusting room temperatures, ventilation, clothing levels and taking baths. To complement in-depth interviews, diaries, audio tours or walkthroughs may be carried out to gain specific insights of how the home is used (Guerra-Santin, O. and Tweed, C., 2015). Also this might reveal how comfort may be negotiated between different occupants (Tweed, C., et al., 2014). Beside to develop a recollection of past practices and other life events, a timeline tool

may be employed (Haines, V., Mitchell, V. and Mallaband, R., 2010). This method may focus on different periods which could be as short as a day, and will allow to ground the discussion using series of events.

To summarise, subjective assessments bring insights into what occupants think they feel or do. Although there are limitations to these methods; namely the 'interviewer-effect' where participants want to please or be perceived in a certain way; then they may alter their responses deliberately. Besides, participants may emphasise some behaviours and not realise that others are more frequent and rooted into daily practices. These omissions may lead to a gap between what people do and what say they do.

2.5.1.2 Objective assessment

Thermal comfort assessment may also use the framework of the predictive approach (ISO 7730:2005) - also known as the heat-balance or PMV model - where occupant comfort is assumed to be a function of physical and physiological parameters. This framework is applied especially to mechanically conditioned buildings (heated and/or cooled), and generally aims to provide uniform environments. The four indoor environmental parameters should be recorded, as ambient air temperature (T_a), mean radiant temperature (T_r), relative humidity (RH) and relative air velocity (v_a). The study design should ideally account for their variations in location and through time although the predictive model is primarily based on steady-state conditions. When the environment is considered heterogeneous (ISO 7726, table 4), the four variables shall be measured at several locations. In particular, the sensors should be placed at standard heights (Table 5 in ISO 7726:2001), defined as ankle, abdomen and head level, set at:

- Sitting position: 0.1m, 0.6m and 1.1m.
- Standing position: 0.1m, 0.6m and 1.7m.

The sensors should be placed in occupied zones where the participants carry out their activities, while avoiding the obstruction of usual circulation in the rooms. Moreover, the potential effect of thermal radiation (e.g. from a heat source such as heaters) and incident solar gains should be taken into account when locating the sensors. With regards to the measurement period, ideally this should be set at 5-minutes or less for at least 2-hours (section 7.3 in ASHRAE 55:2013).

With regards to the instruments chosen to record the four variables, their measuring range, accuracy and precision should comply with the requirements of ISO 7726:2001. However, in practice most studies only deploy one set of sensors in one location; this limits the accuracy of the environmental monitoring results, with assumptions made that the room and/or building retain homogenous conditions and overlooking the potential for any air turbulence or thermal

asymmetry - the latter being explicitly mentioned in the predictive approach as an issue affecting thermal comfort. To address these limitations, recent advancements in more accurate and affordable sensing technologies may allow for the monitoring of building and people, while using discreet observatory systems. Recent studies have used wireless sensor networks to record, store, compute and communicate monitoring data (Tse, W. and Chan, W., 2007), which allows to monitor and control environments in real time.

With regards to the adaptive approach, external dry-bulb temperature should be monitored. Information of a local weather station might be used or the study might deployed sensor(s). A datalogger is placed within a solar shield and collect reading at predefined time intervals. Other outdoor parameters may be monitored, including relative humidity, solar radiation, wind speed and direction. In this approach, it is important to note that the levels and variations in external hygrothermal conditions are associated with the local climate, and also with the neighbourhood built-form and density. Therefore, in addition to hygrothermal recordings, it is important to gain insight into the local site morphology.

2.5.2 Key studies undertaken to date

Existing approaches are based on climate chamber and field study results. For instance, Bedford's series of interviews in 1936 did establish a linear relationship between thermal comfort perception and recorded indoor temperature. This research concluded by setting out an optimum temperature for comfort. Most often, a combination of subjective and objective methods are used, including carrying out questionnaires and measuring environmental variables.

The scope of this research is delineated by three parameters; firstly, the research is set in the UK, secondly, it focuses on dwellings, and thirdly, it takes place in winter. Within these boundary-conditions, a large number of studies have been carried out to date. These vary in their sample size and duration, as shown in Table 2.3. Also, the nature of the studies varies greatly. The studies reviewed in this chapter focused on the following aspects:

- Energy use and carbon emissions in the city's homes (Kane, T. et al., 2011).
- Survey of dwelling temperatures (Hunt, D. and Gidman, M., 1982) (Yohanis, Y and Mondol, J., 2010).
- Assessment of low-energy technologies, specifically from the perspective of domestic refurbishment (Vadodaria, K et al., 2010) (Burris, A., Mitchell, V. and Haines, V., 2012).
- Performance of heating systems and the effectiveness of energy saving measures (Pimbert, S. and Fishman, D., 1981).

- Condensation problems in small modern homes (Oseland, N. and Raw, G., 1991).
- Evaluation of the health impacts of the Warm Front scheme - providing grants to income households for the improvement of home insulation and heating system (Oreszczyn, T. et al., 2006) (Hong, S. et al., 2009).
- Ventilation and heating behaviour in homes (Oseland, N., 1994).
- Human factors and thermal comfort practices in domestic energy consumption (Griffiths, I., 1987) (Tweed, C., et al., 2014).
- Development of a socio-technical model of energy use in buildings (Shipworth, M. et al., 2010).

In all these studies, thermal comfort was not the primary focus but part of the monitoring surveys. Interestingly, all studies have used a mixed-method framework, and most applied the 7-point thermal perception scale.

The study by Pimbert, S. and Fishman, D. (1981) found that when applying the thermal perception scale, 73% of respondents were satisfied; and when applying the thermal preference scale, 90% were satisfied. Also, respondents accepted lower temperatures in their home than at their office. Finally, the preferred temperature in living rooms was set at 23°C to satisfy 90% of the respondents, which is within 22-23 °C CIBSE Guide A recommendations for living room in winter (2006).

Although the study by Hunt, D. and Gidman, M. (1982) did not address thermal perception directly, it investigated clothing and activity levels. The reported mean value for thermal insulation of clothing was found to be 0.86 ± 0.19 clo for men and 0.81 ± 0.18 clo for women. Interestingly, the relationship between clothing level and activity was weak, and a similar result was observed for the relationship between clothing level and dwelling temperature. With regards to activity level, the estimated average metabolic rate was lower for men (69 ± 29 W/m² or 1.19 ± 0.50 met) than for women (81 ± 32 W/m² or 1.39 ± 0.55 met), and the correlation between metabolic rate and dwelling temperature was weak. In summary, clothing level and activities were relatively insensitive to temperature. Similar studies investigating indoor temperature in dwellings have been carried out, although they did not record thermal perception, clothing or activity level (Shipworth, M. et al., 2010) (Yohanis, Y and Mondol, J., 2010) (Kane, T. et al., 2011).

In the study by Oseland, N. and Raw, G. (1991), recorded temperature levels were normally distributed, and ranged between 16 and 22 °C for 81% of homes. Thermal perception

was skewed toward the positive end of the scale, with a mean rating of +1.3, or feeling '*slightly warm*'. The '*neutral*' rating had a corresponding temperature of 18.7 °C. Also, the mean temperature was 19.2 ± 2.68 °C which is almost 3-4 °C lower than the CIBSE Guide A recommendation (2006). With regards to clothing, it was found that respondents adjusted their levels for different temperatures, resulting in similar thermal sensation.

The study by Oseland, N. (1994) reported that the difference between monitored operative, air and mean radiant temperature was minimal. This is an important result for the design of future studies. During the interview, clothing level was reported to be 0.9 ± 0.3 clo in winter. With regards to mean reported and predictive thermal sensation, these were fairly well correlated. Moreover, the results show a difference of 1.1 points in winter, with a mean reported thermal sensation of $+0.6 \pm 1.4$, and a mean predicted thermal sensation of -0.5 ± 0.6 . This led to a difference of 5.4 °C between reported and predicted neutral temperatures, with reported neutral temperature set at 17 °C and predicted neutral temperature set at 22.4 °C. Further analysis reviewed the relationship between temperature and respondent rating, and concluded that the reported neutral temperature should be set at 17.8 °C which is almost 4-5 °C lower than the CIBSE Guide A recommendation (2006)

The study by Hong, S. et al. (2009) reviewed the effect of retrofit measures. Results show that perceived thermal comfort increased post-retrofit. There was a difference of 0.5 points between mean reported and predictive thermal sensation, which led to a 1.5 °C difference in reported and predictive neutral temperature, with reported neutral temperature set at 18.9 °C and predicted neutral temperature set at 20.4 °C. The level of clothing decreased post-retrofit from a mean of 0.82 clo to 0.75 clo once insulation and a new heating system were installed. Mean activity level was set at 1.35 ± 0.18 met. Finally, no significant relationship was found between perceived thermal comfort and external temperature.

Although the studies reviewed above have uncovered interesting insights into the evaluation of perceived thermal comfort, and the calculation of neutral temperature, little has been studied on thermal adaptation. The study by Burris, A., Mitchell, V. and Haines, V. (2012) was aiming to gain an understanding of how and why occupants create comfort at home. Here 'comfort' touches many themes, including thermal, surroundings, physical, entertainment, food, state and visual. With regards to thermal comfort behaviour-adjustments, these include turning on/off the heating system, using a fireplace, adapting clothing level, or bathing. Moreover, it is highlighted that fireplace may not only be used to alleviate cold but also to bring a feeling of warmth. Another study by Tweed, C., et al. (2014) reports on thermal comfort practices and energy consumption in five dwellings in South Wales. Interestingly the study carried out a mixed-method

approach with series of in-depth interviews, audio tours, telephone surveys and environmental monitoring. The householders developed a range of behaviours to achieve comfort, including additional clothing, covers, hot drinks, interacting with the heating system (TRVs, thermostat set-point, timer, manual control), zoning system and portable heaters. The study concluded that occupants had very different thermal comfort ideals and ways in achieving those.

2.6 Summary

The notion of comfort may be defined as a "*socio-historical artefact*", which can be described as an attribute or an achievement (Hinton, E., 2010). Thermal comfort in particular maybe be defined as "*that condition of mind which expresses satisfaction with the thermal environment*" (ASHRAE 55:2013). Here thermal comfort is considered to be an attribute of the dwelling, and can be technically specified and assessed. The development of thermal comfort standards has been driven by engineers and physicists providing for the establishment of heating and ventilation systems. The current framework fails to engage actively with the occupants, and only strive to specify tight ranges of hygrothermal conditions. In contrast, more recent studies have recognise people as agents using different heating practices to achieve comfort. In this perceptive, comfort is an achievement influenced by past experiences but also economical, social and cultural attributes. People create their own comfort in various ways and for various reasons.

The current thermal comfort approaches can identify issues within the thermal environment, but occupants' predicted level of perceived comfort is less accurate. Moreover, little is known about thermal adaptation, in particular psychological and behavioural adaptation, which rely on people's accounts. The purpose of this research is to develop a method to monitor people's thermal discomfort responses in their home. The dynamics between people and their dwellings' thermal comfort systems form a complex framework, and people's responses may be influenced by a range of factors, including soci-demographics, economics, perceived controls, etc. Having reviewed literature on thermal adaptation and the current assessment approaches to evaluate thermal comfort, the next chapter will draw the framework of the research to be applied in empirical studies.

Table 2.3: Key published studies, evaluating winter thermal comfort in UK's dwellings

Source	Name of the study	Data collection methods (EV)	Data collection methods (PV)	Sample (no. of participants)	Location	Duration
Pimbert and Fishman, 1981		Indoor and outdoor temperature	Questionnaires (7pt scale, thermal preference and clothing level) and interviews	2 surveys (33+7)	London and Washington	Oct.-Feb.
Hunt and Gidman, 1982	National field survey	Indoor and outdoor temperature	Questionnaires (clothing and activity level)	901	50 towns and cites in the UK	Feb.-Mar. 1978
Griffiths, 1987	Human Factors in Domestic Gas Consumption in South-East England, 1981-1985	Surveys of physical and structural house characteristics and temperature measurements	Interviews and postal surveys	Intensive sample 140, Extensive sample 1,160		Dec. 1983 - May 1985
Oseland and Raw, 1991	BRE survey of "starter homes"	Indoor temperature	Questionnaires (7-pt scale, clothing level)	383	7 regions in the UK	Winter 1986-87
Oseland, 1994	BRE survey	Indoor and outdoor temperature (operative, air, wet bulb)	Questionnaires (7pt-scale, thermal preference, clothing level),	515	8 areas in the UK	Winter 1991-92
Oreszczyn et al., 2006 and Hong et al., 2009	Warm Front Study	Building surveys and Indoor and outdoor temperature	Questionnaires and diaries (7pt-scale, clothing and activity level)	2,399	5 cities in England	2-4 weeks over 2 winters 2001-2003
Yohanis et al., 2010	Northern Ireland Housing & NIE	Indoor and outdoor temperature	Questionnaires (socio-demographic, occupancy, 7pt-scale)	25	Northern Ireland	Feb. 2004 - Jan. 2005
Vadodaria, 2010 and Burris, 2012	CALEBRE project	Temperature and humidity	Interviews	66 and 33	East Midlands	
Shipworth et al., 2010	CaRB project	Indoor and outdoor temperature	Interviews (building, socio-demographic)	427	Stratified random sample, England	Jul. 2007 - Feb. 2008
Kane et al., 2011	4M project	Indoor and outdoor temperature	Interviews (building, socio-demographic)	290	Leicester	9 months 2009-2010
Tweed et al., 2014	Carbon, Control and Comfort project	Indoor and outdoor temperature and humidity	Window opening, telephone survey and interviews	5	South Wales	5 days in Feb. and Aug. 2011

(EV) Environmental variables

(PV) Personal variables

Chapter 3

Research Design

3.1 Research question, aims and objectives

Drawing on from the literature review, only a few studies have reviewed the range and impact of behavioural responses to thermal discomfort. These studies have mostly focused on occupants interactions with the comfort systems, including window opening and thermostat controls, and on the use of clothing. However, little is known about the frequency of the occupants activity level, food and liquid intake or other localised behaviour. To address this issue, research presented in this PhD thesis aims to propose a framework to identify variations and frequencies of peoples responses to cold thermal discomfort in UKs dwellings. The context of this research is set in domestic settings, referred to as free-living environments and defined by Vega-Gonzalez, A. and Granat, M. (2005) as '*continuous quantification of movement in natural settings while the participant/patient performs his/her everyday activities*'.

The research question was formulated as follows:

How are people responding to cold thermal discomfort in their homes?

To answer this question, the aims of the thesis are as follow:

- To report on an evaluation of the sensitivities of the current thermal comfort models.
- To develop a set of methods to estimate metabolic rate (M) and thermal insulation of clothing (I_{cl}) as objective, quantitative and continuous variables in free-living environments.
- To develop a set of methods to gather people's responses to thermal discomfort in free-living environments at a fine temporal resolution.
- To develop a framework to monitor thermal discomfort responses that incorporates a wider range of observed behaviours.

The first aim described above was converted into the following objectives:

- To provide an insight of how the models dependent variables respond to changes in their independent variables.
- To assess which inputs have the most and the least influence on the outputs and, consequently, to ascertain which independent variables should be determined with greater precision and accuracy.

The second aim of the thesis was translated into the following objectives:

- To review and evaluate the existing methods to estimate (M) and (I_{cl}).
- To adopt the most suitable approach for the investigation of the specific research question, informed by the literature review.
- To identify a set of case studies, and carry out an empirical study (data collection).
- To collate these data into a comprehensive dataset (data processing).
- To develop an analysis method that will assign values to (M) and (I_{cl}) (data analysis).

The third aim of the thesis was translated into the following objectives:

- To review and evaluate existing methods of monitoring peoples thermal behavioural adaptation.
- To adopt the most suitable approach for the investigation of the specific research question, informed by the literature review.
- To identify a set of case studies, and carry out an empirical study (data collection).
- To collate these data into a comprehensive dataset (data processing).
- To develop an analysis method that will (1) identify occupants responses to cold discomfort, and (2) quantify the frequency of occurrence of these responses (data analysis).

Finally the fourth aim of the thesis was associated with the following objectives:

- To develop a framework that will be able to assess the contribution of adaptive behaviours.
- To review the internal and external validity of the proposed framework.

3.2 Research design requirements

The key intention of this research is to develop a method to monitor thermal discomfort response variability, and identify adaptive behavioural patterns. The most influential parameters, as encompassed in the adaptive and predictive approaches require:

- Estimation of two personal factors: metabolic rate, and thermal insulation of clothing.
- Measurement of five environmental factors: running mean external temperature, dry-bulb air temperature, mean radiant temperature, relative humidity, and relative air velocity;

In current field studies, the values given to the personal variables are usually estimated from observation (de Dear, R., Brager, G. and Cooper, D., 1997). This estimation holds great uncertainty, which reduces the precision of the predictive models results. Consequently, it is critical to be able to determine those factors with greater precision and accuracy. One of the key intentions of this research is to gather these measurements while using discreet observatory systems that have minimum impact on the occupants behaviour. The research design aimed to minimise the potential impact of the Hawthorne effect, where participants may alter their behaviour in response to their awareness of being observed. With recent emergence of, and advancements in, more accurate and affordable sensing technologies, this problem can potentially be overcome.

Most thermal comfort studies conducted in the field have used sensing stations and taken measurements at a single location over short periods of time, from 1 to 60 minutes (de Dear, R., Brager, G. and Cooper, D., 1997) (Brager, G. and de Dear, R., 1998) (Mishra, A. and Ramgopal, M., 2013). Recent studies carried out in UK dwellings used multiple dataloggers; in most cases one was used in the bedroom and one in the living room, and measurements were taken over longer periods of time, and at short intervals (Hong, S. et al., 2009) (Shipworth, M. et al., 2010) (Kane, T. et al., 2011). Although these studies measure only two environmental variables (T_a) and (RH), dataloggers are the preferred method for field study deployments, as they are less obtrusive and costly than sensing stations.

Thermal comfort can also be affected by other factors that do not relate directly to the thermal environment; these include psychological factors such as perception of control over the heating system. These factors may be captured using questionnaires, interviews and visual diaries.

In summary, the research design should include the requirements listed in table 3.1, which included data sensing, and logging. The requirements were grouped using the MoSCoW prioritisation method (Hatton, S., 2008) (Onipko, A., 2011).

Table 3.1: Research design requirements for the data gathering phase

No.	Requirement	Priority
1	To collect information on the building, including: location, age, fabric, heating system, energy performance rating, etc.	Must Have
2	To collect information on the occupant(s), including socio-demographic information, subjective accounts toward their thermal environments, and time-use diary.	Must Have
3	To allow discreet observations and measurements	Must Have
4	To measure metabolic rate	Must Have
5	To measure thermal insulation of clothing	Must Have
6	To measure dry bulb temperature	Must Have
7	To measure relative humidity	Must Have
8	To store the measured data, and to enable download	Must Have
9	To have multiple sensing nodes	Must Have
10	To allow synchronisation of all sensing nodes	Must Have
11	To measure relative air velocity	Should Have
12	To have sensors condition monitoring	Should Have
13	To optimise energy used for sensor's operation	Should Have
14	To measure running mean external temperature	Could Have
15	To measure mean radiant temperature	Could Have
16	To have a wireless sensing system, where nodes communicate between each other	Won't Have
17	To allow real-time network monitoring	Won't Have

'Must Have' *High priority requirements that are fundamental to the research.*

'Should Have' *Medium priority requirements that would be nice to have.*

'Could Have' *Low priority requirements that would be nice to have, but can be omitted due to resource availability.*

'Won't Have' *Low priority requirements that are not appropriate at the current state of the project.*

Having gathered the required information, the output should be analysed to answer the research question and associated aims and objectives, in particular:

- To identify the different types of reported, predicted and actual responses toward thermal discomfort.
- To identify the variations and frequency of responses to cold thermal discomfort in dwellings.

Having set the research design requirements, the following chapters will (1) review the current methods used to assess behavioural adaptation, (2) introduce the approach to be implemented in a series of case-studies, and (3) conclude by introducing a new framework to monitor thermal discomfort response variability.

3.3 Sampling

3.3.1 Recruitment of participants

The field studies relied on recruiting 31-participants from 29-dwellings. Into the sample frame, 11-participants joined the pilot study, and 20-participants joined the main study. 32-participants started the study, and 31-participants completed it; this is equivalent to a 3% dropout rate. This study applies focal-sampling as specific individuals were observed for a set period of time.

In the pilot study participants were recruited through a call for participation sent out to friends and colleagues; these had varied occupation, ranging from unemployed, academics, architects, engineers, office workers and students. Recipients of the email were encouraged to forward on the announcement. No incentive was offered.

In the main study, participants were recruited through a call for participation sent out to the University College London (UCL) mailing lists. Recipients of the email were encouraged to share the announcement within their networks. No incentive was offered. As a consequence, the majority of the participants were UCL academics, administrative members of staff, or students. The number of participants was set at 20 case-studies, to fulfil the requirement of minimum sample-size set by Warren, C. (2002). This minimum level is important to support the emerging conclusions of the study; however this sample size is small, and does not intend to be statistically representative. The aim of this research is to develop a method to monitor thermal discomfort response variability.

This study relied on theoretical criteria rather than statistical ones, due to field-work constraints, mainly resources, cost and time. The basis of theoretical sampling is grounded in theory. In this research people are observed at different times of day, and in different contexts - at home alone or socialising. The aim is to develop a method to map thermal discomfort responses in a free-living environment, and to discover type and frequency of responses. The research is concerned with the refinement of a hypothesis about the way people respond to thermal discomfort, rather than a large sample size. To this effect, qualitative and quantitative information is collected through a mixed-method framework, using environmental monitoring, visual diaries, questionnaires and interviews. This process is partly controlled by emerging theory; for example, the outcome of the pilot study steered the choice of sampling frame in

the main study. Also, the monitoring instruments allowed continuous periods of observation, which enabled frequency and duration of specific behaviours to be measured. With regards to uncovering the type and frequency of responses, some theoretical saturation should be reached by the end of the data collection, to identify the singularity, property, dimension and importance of each response category. With regards to gaining access to private environments, two aspects were considered:

- Gaining access - the recruiting-email and information sheet had to provide clear explanations of duration, aim and methods of the study.
- Ongoing access - once the first contact with the participant was made, it was important to clarify what was the researcher's role, their credential, non-judgmental role, and the confidential nature of the research.

3.3.2 Sampling frame

The case study sample frame was chosen purposively to maximise diversity of factors of interest, and minimise variation in contextual conditions.

The aim of the pilot was to test the mixed-method framework and assess the range of variables to collect, in particular the socio-demographic and dwelling characteristics. The sampling frame primary variables were defined as qualitative and mutually exclusive. Their selection was based on previous thermal comfort studies, and included:

- Socio-demographic characteristics: participants' genders and participants' patterns of use of the home in particular their occupation, the number of occupants and relationship status. A study by Karjalainen, S. (2007) shows significant gender differences in thermal perception, temperature preference, and use of thermostats. Whereas patterns of use have been shown to have an influence on heating demand (DECC, 2012a).
- Dwelling characteristics: built forms, ages, and heating systems. These variable are particularly influential to space heating demand (Hughes, M. et al., 2013).

Details of the participants locations and monitoring periods are shown in table 3.2. All participants were scattered within Greater London, various locations were chosen to account for potential micro-climatic effects. Not all respondents would show some commonality, yet they all display singularity for one of the primary characteristics of the study, as they were chosen to maximise diversity of factor of interest. The analysis reviewed the types and frequency of responses to thermal discomfort for all participants with associated conditions.

Table 3.2: Pilot study - monitoring period and dwelling location for each participant

Participants	Area Code ¹	Monitoring starting date	Monitoring ending date
P01	SW5	28-10-2010	30-10-2010
P02	W6	30-10-2010	02-11-2010
P03	N19	04-11-2010	06-11-2010
P04	SE16	06-11-2010	10-11-2010
P05	SW19	14-11-2010	16-11-2010
P06	NW6	18-11-2010	20-11-2010
P07²	N7	20-11-2010	23-11-2010
P08	N5	25-11-2010	27-11-2010
P09	NW1	27-11-2010	30-11-2010
P10	N20	02-12-2010	04-12-2010
P11²	N7	04-12-2010	07-12-2010

¹ The dwelling locations are identified by the area code and not the full post code to comply with ethical approval requirements, and to ensure confidentiality.

² Participants leaving in the same dwelling.

The full study aimed to test the refined mixed-method framework through a sample frame based on three physiological criteria; gender, age and weight. As defined by ISO 8996:2004 (Annex C), these variables have a direct influence on the estimation of metabolic rate, which is the most influential variable in the PMV predictive model. Although convenience-sampling was used, participants were selected to ensure a 'spread' of the 3-primary criteria. As show in table 3.3, participants lived in different location within the South-East of England, mostly focus within Greater London. This study relied on theoretical criteria rather than statistical representativeness due to fieldwork constraints, in particular limited access to resources, and the time constraint of the project.

Table 3.3: Main study - monitoring period and dwelling location for each participant

Participants	Area Code¹	Monitoring starting date	Monitoring ending date
P01	NW1	26-01-2012	06-02-2012
P02	WD24	01-02-2012	13-02-2012
P03	SW2	02-02-2012	13-02-2012
P04	NW1	08-02-2012	20-02-2012
P05	WD17	23-02-2012	05-03-2012
P06	SW4	23-02-2012	05-03-2012
P07	WC1H	29-02-2012	12-03-2012
P08	NW1	05-03-2012	20-03-2012
P09	WC1H	08-03-2012	19-03-2012
P10	N17	25-10-2012	05-11-2012
P11	N20	30-10-2012	09-11-2012
P12	KT1	05-11-2012	19-11-2012
P13	TW1	10-11-2012	20-11-2012
P14²	OX2	12-11-2012	23-11-2012
P15²	OX2	12-11-2012	23-11-2012
P16	N17	19-11-2012	03-12-2012
P17	N19	26-11-2012	08-12-2012
P18	E14	28-11-2012	13-12-2012
P19	N22	03-12-2012	20-12-2012
P20	SW19	08-12-2012	18-12-2012

¹ The dwelling locations are identified by the area code and not the full post code to comply with ethical approval requirements, and to ensure confidentiality.

² Participants leaving in the same dwelling.

3.4 Ethical Considerations

All research involving participants should conform within the standards set-out by the research institution. The pilot study and main study were registered with UCL data protection, and approved by UCL Research Ethics Committee before research commenced (Ethics Application 4189/001).

3.4.1 Planning the field studies

As highlighted in the UCL Research Ethics Committee - Guidelines on Completing the Application Form (2014), most of the ethical issues result from relationships and the risks involved, there is important to clarify the following:

- What obligations does the researcher have to the participants?
- What obligations do the participants have to each other?
- Are participants or researchers at risk?

In connection to who will have access to the information, participants identities should be kept confidential, whereby only the research-team has access to the recruitment information. These records should be destroyed at the end of the research project.

With respect to privacy levels, procedures should be put in place so that participants can safely share their experiences and opinions. For example, a focus-group involves sharing information with the groups participants; in this case privacy is one of the central concerns as to what the participants reveal during the discussion. Each interaction involves a degree of self-disclosure, and potential for over-disclosure when one person reveals a damaging personal fact or opinion. To alleviate some of the concerns, participants may be identified by their first names or use pseudonyms. In addition, the moderator should be trained to recognise early signs of stress, and should also raise the issue at the start of the session; for example, the moderator may say: *"Some of the topics that you will be discussing today can be sensitive and personal. We don't want you to feel stressed by this discussion. So, if I sense any of this, I will have us take a little break, relax for a minute, and then start up again at a level where everyone feels comfortable."* (Morgan, D. and Krueger, R., 1998) (p93).

With regards to focus-groups or interview transcripts, names and other identifying information should be removed or modified.

3.4.2 Ethical requirements

As the research involved '*living human participants*', it required ethical approval to ensure that the research conformed with UCL general ethical principles and standards.

This research used a recently developed tool allowing the daily capture of pictures from an automated wearable camera. Kelly, P. et al. (2013) reviewed ethical frameworks for automated visual diaries; implications of such research include:

- Extensive collection of information. Confidentiality was ensured as the pictures were only accessible to the researcher, and supervisors upon request. The electronic files were password-protected and stored securely. The information should be deleted/destroyed when no longer required for the research project.
- Passive image capture. The pictures were taken by changes in sensors output and by timer therefore unwanted pictures may be taken. This was made explicit in the informed consent. Full disclosure of all the information collected was made available to the participants for review and confirmation of permission to retain the data. The device was also fitted with a privacy button allowing a 7-minute pause. At any time the participant could stop the recording by switching off the device or covering the camera lens.
- Third party. As the research took place in homes, family members, cohabitants and friends may have been included in the pictures. Although written informed consent may not be necessary, it was important to seek their verbal permission. This was done when visiting the home, although all party may not have been present; therefore, information and handouts were provided to help the participants, explaining that photographs will be taken but securely stored and not disseminated.
- Dissemination of information. When used for presentations and publications, imagery material needed additional consent from the participant; illustration was then reviewed image by image. Also pixelation techniques were employed.

The main aim of this approval process is to minimise the risk of harm and to protect the researcher and the participants. As this research was to include collection of visual information, additional considerations should be taken (Prosser, J., Clark, A. and Wiles, R., 2008) (Davies, K., 2008). UCL's four ethical standards forms include:

- Information sheet - Prior to agreeing to take part in the study the participant should have understand why the research is being done and what it will involve (see Appendix A). The Information sheet provides a detailed description of the study, including its purpose,

the data collection process, the benefit of taking part, insurance of confidentiality, who has access to the data, contact details, and what will happen to the results of the research study.

- Informed consent - After agreeing to take part and before the start of the data collection, the participant and the researcher should review and signed the consent form (see Appendix A). This joint agreement states the rules or boundary conditions of the research, including:
 - Having understood the information sheet and what is involved in the study.
 - The voluntary nature of the study.
 - The withdraw process.
 - The system in place to ensure confidentiality.
 - Who has access to the data, which will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.
 - How data will be retained (security) and for how long.
 - How the data will be used in presentations and publications - including additional consent for imagery material where illustrations will be reviewed image by image.
 - Confirming participation in the research.
- Confidentiality - information provided will be held confidentially, such that only the researcher can trace this information back to the participant. A name coding system and pixelation of photos will be used.
- Benefit not harm (Risk assessment).

With regards to the participants, the study does not include children or vulnerable adults. The sample criteria was first chosen to test the data collection method, then to conform to the criteria set by EN ISO 8996:2004 Annex C, as gender, age (20 to 60 years), and weight (50 to 90 kg). No third party information was used.

3.4.3 Data protection requirements

As the research uses personal data, the project was registered with the UCL Protection Officer (see Appendix B). The application included details of the project and the participants, the disclosure procedure for the collected data and publication of the results, and details of consent.

Participants had access to their data and could find out what had been done with it at any time. With regards to storing the information, electronic personal data were only stored on

portable devices owned by UCL and were password protected. Manual personal data was kept on UCL premises most of the time, and always in locked units.

The study was registered with UCL data protection every year, under the following registration reference numbers:

- no Z6364106/2010/10/39 (section 19, research: social research) for the pilot study, October to December 2010.
- no Z6364106/2012/01/21 (Section 19, research: social research) for the main study, January to March 2012.
- no Z6364106/2012/08/65 (Section 19, research: social research) for the main study, October 2012 to February 2013.

3.4.4 Risk assessment requirements

The field work has low risk associated with it; to this effect the UCL risk assessment form has been completed (see Appendix B), and associated procedures followed. Even though the participants were part of UCL staff and student community or friends, the following contact arrangement procedure is followed:

- Visit log was issued before each visit to the Departments Designated Person (DDP), including participant details.
- Contact arrangement procedure via mobile phone text followed, as:
 - The researcher sent a text message to the DDP upon arrival.
 - The researcher will set an alarm and text the DDP 1.5 hour after arrival: (1) to confirm that the visit did finish and that all is fine; (2) to extend the visit time by 1 hour.
 - If the visit was extended, the researcher will set an alarm and text the DDP 2.5 hours after arrival: (1) to confirm that the visit did finish and that all is fine; (2) to extend the visit time by 1 hour.
 - (step 2.3 may be repeated until the visit finishes).

The participants did not take part in any activity that may have been potentially stressful or harmful throughout the research; the interview and focus group did not raised any sensitive, embarrassing, or upsetting topics or issues. The procedures involved were not invasive, and did not involve physical contact.

To follow UCL risk assessment procedure, in case of emergencies the researchers contact details were given in the introductory email and information sheet. The monitoring equipment had proprietary manufacturers warranties and did not hold any foreseeable risks, discomfort or inconvenience. During the first visit the participants were advised of the correct use of the equipment; in addition user's guides were handed over to the participants.

3.5 Summary

This chapter reviewed the research's aims and objectives, and associated research design requirements, sampling and ethical considerations. This research proposes to use a set of methods, with the intention to create links between the different approaches and their output. Standard methods used to assess thermal perception are combined with recent techniques such as automated visual diaries. This combination of methods was assessed in a pilot study, and will be discussed in more detail in the following chapter.

Chapter 4

Estimating activity and clothing level

4.1 Outline

To follow the aims and objectives set out in the introduction, this chapter will first carry out an evaluation of the global sensitivity of the models described in standards and guidelines. This will identify which factors should be most accurately and precisely measured in the empirical study. Results show that metabolic rate and clothing insulation level are the most influential variables. In the second part of this chapter, methods will be developed and tested to measure these two personal variables objectively and quantitatively.

4.2 Sensitivity analysis of the standard thermal comfort models

The aim of this chapter is to report on an evaluation of the sensitivity of the standard thermal-comfort models to assess indoor cold thermal discomfort, therefore outdoor and heat indices will not be reviewed. The results of this analysis should reveal crucial insights on the current models, and influence the choice of methodological framework to monitor people's responses to thermal discomfort. The thermal comfort models encompassed in current standards are of two types: adaptive and predictive models.

Adaptive models are derived from empirical studies, and assume that occupants' preferred indoor temperature or operative temperature (T_{ot}) varies with external weather conditions. Therefore people's behaviour may vary according to the different seasons and occupants are given time and opportunity to adapt to their environment. Intended for naturally ventilated buildings, these models are part of the ASHRAE 55:2013 and the EN 15251:2007.

The second type of thermal comfort model is based on physical and physiological properties. The most notable models are the Fanger model (one-node) (Fanger, P., 1970), Pierce model (two-nodes) (Gagge, A. et al., 1986), and Kansas State University model (two-nodes) (Azer, N. Hsu, S., 1977). These differ in the physiological models employed and the criteria

used to predict thermal sensation. Described in ASHRAE 55:2013, EN15251:2007, and ISO 7730:2005, the indices associated with these models are as follows:

- Predictive Mean Vote (PMV) is the predicted thermal sensation of a group of persons. Derived from Fanger's one-node model, it is rated on a 7-point scale. ISO 7730:2005 Annex D and ASHRAE 55:2013 Appendix B included a computer code to carry out the calculation.
- New effective temperature (ET^*) provides a method to determine the relative effect of air temperature, and humidity. It was developed using the two-nodes model - (Gagge, A. et al., 1986) as modified by Doherty, T. and Arens, E. (1988), and described in ASHRAE Handbook of Fundamentals (2009).
- Standard effective temperature (SET) is used to evaluate thermal sensation of occupants, in particular for elevated air speeds above 0.2 m/s as prescribed by ASHRAE 55:2013 section 5.3.3. This index was developed using the two-nodes model - (Gagge, A. et al., 1986) as modified by Doherty, T. and Arens, E. (1988). ASHRAE 55:2013 Appendix G includes a computer code to carry out the calculation.
- Thermal sensation (TSENS) and thermal discomfort (DISC) are two other indices derived from the two-nodes model (Gagge, A. et al., 1986) (Doherty, T. and Arens, E., 1988). Based on an 11-points scale, they are not part of the current standard but are included in building energy simulation assessment (Fountain, M. and Huizenga, C., 1997) (US Department of Energy, 2012). TSENS is defined as the deviation of the mean body temperature from cold and hot set-points, while DISC includes the Winslow's Skin 'Wettedness' Index, when the mean body temperature is above the cold set point (ASHRAE, 2009).
- PMV_{ET^*} and PMV_{SET} are two indices derived from the PMV model and using ET^* and SET instead of operative temperature (Gagge, A. et al., 1986). They are not part of the current standard but are included in building energy simulation assessment (US Department of Energy, 2012).

The models are applied to mechanically conditioned buildings (heated and cooled). Developed from laboratory experiments in climate chambers, the predictive approaches combine knowledge of the human bodies physiology and of heat-transfer theory. Indices' independent variables include:

- Four measured environmental variables (*EV*), including: ambient air temperature (T_a), mean radiant temperature (T_r), relative humidity (RH) and air velocity (V_a).
- Two estimated personal variables (*PV*), including: metabolic rate (M) and thermal insulation of clothing (I_{cl}).

Methods for the measurement and the estimation of the six independent variables are set in the following standards:

- ISO 7726:2001 addresses the minimum characteristics of instrumentation to be used to measure the four environmental factors.
- ISO 8996:2004 reviews four methods used to assess metabolic rate.
- ISO 9920:2009 determines the assessment of thermo-physical properties of clothing ensembles.

Although these models have been developed and used for the last forty years, only a few sensitivity analyses have been completed. With regards to the predictive models, little is known as to what influence each of the six independent variables has in the calculation of dependent variables, PMV , ET^* , PMV_{ET^*} , SET , PMV_{SET} , $DISC$ and $TSENS$. Previous studies employed differential sensitivity analyses to evaluate the accuracy of the independent variables (Alfano, G., Romana dAmbrosio, F. and Riccio, G., 2001) (D'Ambrosio Alfano, F., Palella, B. and Riccio, G., 2011). However, this analysis technique has limitations, including:

- Establishing a base level where $PMV = 0$, and a list of associated input-values for each variable. The justification for these chosen inputs-values remains questionable, as there are many combinations resulting in $PMV = 0$. Why would one combination of inputs be chosen over another one? This question remains open, as it was not answered in previous studies.
- Assuming that the model is linear or additive.
- Assuming that the input variables are independent from one another.

To address some of these issues, this research uses global-sensitivity techniques, in particular the Monte Carlo analysis. This technique aims to provide insights of how the model dependent variables respond to changes in the independent variable(s), and to assess which inputs have the most and the least influence on the output. Finally this study will determine where the models uncertainties are coming from, and expand current knowledge and confidence in the thermal models and its models' output.

The Monte Carlo analysis is a stochastic tool, used to simulate the simultaneous change of all inputs. It aims to quantify the uncertainty of the dependent variable caused by the uncertainty of the independent input variables (Lomas, K. and Eppel, H., 1992) (Saltelli, A. et al., 2004). This method allows the determination of the interaction among variables, while not making any assumptions on the additive effects of the inputs. However, as the inputs are varied simultaneously, the sensitivity of an individual input parameter cannot be revealed. The following analysis uses a five-step process (Saltelli, A., Chan, K. and Scott, E., 2000) as described below:

- Selection of the ranges and the distributions of the model variables.
- Generation of a random sample of the model variables.
- Evaluation of the model for each variable input.
- Uncertainty analysis.
- Sensitivity analysis.

4.2.1 Independent variables ranges and distributions

The adaptive models are based on linear relationships between its input, the running mean outdoor air dry-bulb temperature (T_o), and its output, the operative temperature (T_{ot}). On the other hand, the predictive models have six independent variables and five associated indices, as PMV , ET^* , PMV_{ET^*} , SET , PMV_{SET} , $DISC$ and $TSENS$. Using a framework by (Saltelli, A., Chan, K. and Scott, E., 2000), the ranges and the values of the input variables are described in Table 4.1.

In this analysis, the ranges selected for each independent variable are derived from ISO 7730:2005 (section 4.1). The input values to the environmental variables were determined by reviewing the required accuracy in ISO 7726:2001. These accuracy values were then used to determine the increment values. For the personal variables, the increment of each input value was determined by reviewing ISO 7730:2005 Annex B and Annex C.

Table 4.1: Characteristics of the independent variables of the predictive models

	Independent variables			Selected ranges ¹	Increment values ²	No. of possible inputs values
EV	Air dry-bulb temperature	(T_a)	$^{\circ}C$	[10,30]	0.5	41
	Mean radiant temperature	(T_r)	$^{\circ}C$	[10,40]	2	16
	Water vapour partial pressure	(P_a)	Pa	[0,2700]	150	-
	Relative humidity ³	(RH)	%	[0,100]	5	21
	Relative air velocity	(V_a)	m/s	[0,1]	0.05+0.05 V_a	16
PV	Metabolic rate ⁴	(M)	met	[0.8,4]	0.1	33
	Effective mechanical power	(W)	(W/m^2)	[0]	0	1
	Thermal insulation of clothing ⁵	(I_{cl})	clo	[0,2]	0.1	21

(1) ISO 7730:2005, section 4.1.

(2) ISO 7726:2001 for the environmental variables, and ISO 7730:2005 Annex B and C for the personal variables.

(3) RH is a function of (T_a) and (P_a) , as per the Antoine equation Gagge, A., Stolwijk, J. and Hardy, J. (1976).

(4) With 1 met = 58.2 W/m²

(5) With 1 clo = 0.155 m².K/W

The analysis includes the sensitivity of the predictive models as taken from the standard and does not assume any prior distribution of its variables. Therefore **uniform distributions** were assumed for all independent variables. It is worth noting that sensitivity analysis is more responsive to the selected ranges than to the distribution of the variables (Saltelli, A., Chan, K. and Scott, E., 2000). By following the assumption taken for the ranges, the increment values and the distributions, the total number of possible combinations of the 6-independent variables amounts to 152,748,288. This defines the space where the sample can be drawn from.

4.2.2 Sampling

The second step in the analysis involves the selection of a sample drawn from the selected distributions. Assuming that the variables are independent of each other, the same weighting is given to each input value. The number of iterations is determined using a 95% confidence level for each indices, and following the methods presented in (Bevrani, H. Ghorbani, M. and

Sadaghiani, M., 2008). As a result of this analysis, a random sample of 10,000 inputs for each variable is generated. This large sample size strengthens the power of the analysis, and increases the precision when estimating correlation coefficients. The random sampling process estimates mean and variance of the independent variables, PMV , ET^* , PMV_{ET^*} , SET , PMV_{SET} , $DISC$ and $TSENS$.

4.2.3 Evaluation of the predictive models

The selected sample inputs are given to the models, generating a sequence of outcome values to PMV , ET^* , PMV_{ET^*} , SET , PMV_{SET} , $DISC$ and $TSENS$; these are summarised in Table 4.2 and Figure 4.1.

Figure 4.1: Density distributions of the predictive model indices

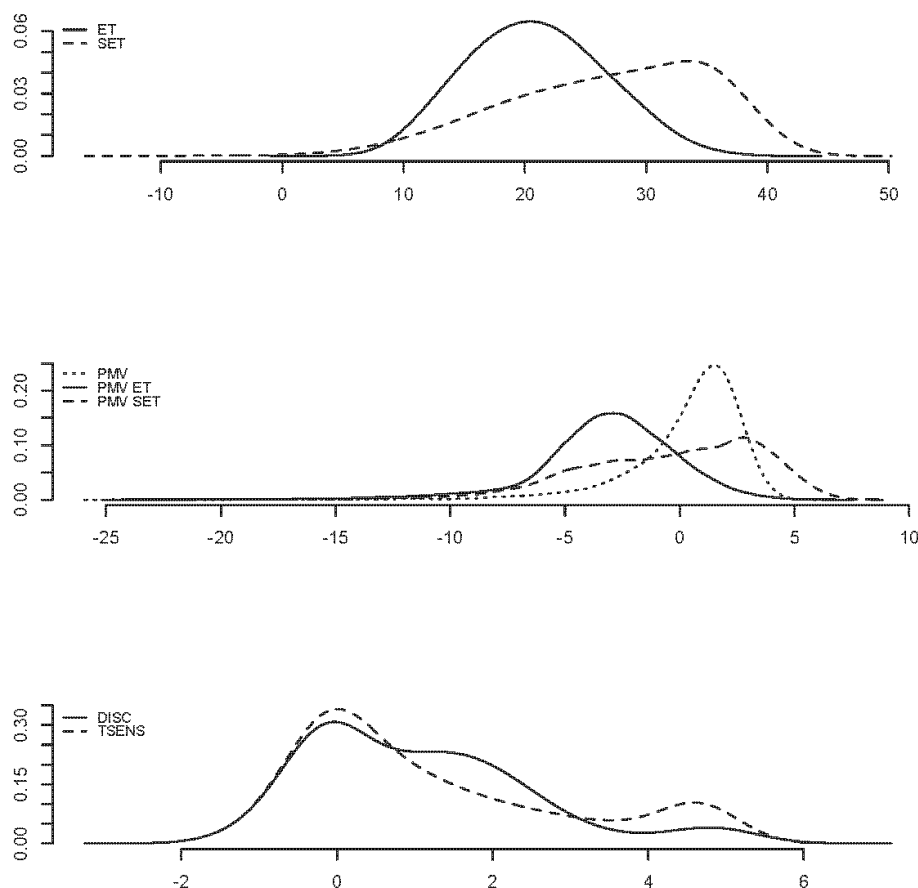


Figure 4.1 shows the results of the predictive models, with indicative kernel density estimation inferred from the density distributions. Having carried out a Shapiro-Wilk test on the indices-output, only ET^* is normally distributed. Moreover $DISC$ and $TSENS$ are multimodal, which reflects the cold and hot set-point introduced in their calculations.

Table 4.2: Summary of the statistical characteristics of the distribution of ET^* , SET , PMV , PMV_{ET^*} , PMV_{SET} , $DISC$ and $TSENS$

		ET^*	SET	PMV	PMV_{ET^*}	PMV_{SET}	$DISC$	$TSENS$
CT^1	Mean	20.91	26.89	0.33	-3.17	-0.46	1.05	1.21
	Median	20.75	27.99	0.96	-2.92	0.20	0.83	0.60
Spread	Variance	30.4	72.06	6.65	9.81	16.43	2.04	2.95
	Standard deviation	5.51	8.49	2.58	3.13	4.05	1.43	1.72
	Maximum	38.43	44.21	5.07	6.11	7.72	5.63	4.70
	Minimum	5.04	-10.27	-24.43	-23.69	-22.83	-1.74	-1.74
	Range	33.39	54.48	29.50	29.8	30.55	7.37	6.44
	Quantile (.75)	24.73	33.78	1.93	-1.23	2.72	1.87	2.20
	Quantile (.25)	16.82	21.02	-0.51	-4.62	-3.08	-0.08	-0.08
Shape	Skewness	0.17	-55	-2.40	-1.13	-0.89	0.96	0.89
	Kurtosis	2.57	2.83	12.74	6.34	4.26	3.63	2.56

CT^1 : Central Tendency

Table 4.3: Thresholds of thermal sensations (TS) used in predictive indices

TS	ET^*		SET		PMV		PMV_{ET^*}		PMV_{SET}		$DISC$		$TSENS$	
	T	(%)	T	(%)	T	(%)	T	(%)	T	(%)	T	(%)	T	(%)
Int. cold	.	.	.	.	.	.	.	.	.	.	-5	0	-5	0
Very cold	.	.	.	.	.	.	.	.	.	.	-4	0	-4	0
Cold	.	.	.	.	-3	10	-3	57	-3	30	-3	0	-3	0
Cool	<20	45	<17	14	-2	6	-2	15	-2	7	-2	0	-2	0
Slightly Cool	.	.	17-30	44	-1	9	-1	11	-1	8	-1	7	-1	8
Neutral	20-28	44	30-34	18	0	15	0	8	0	8	0	40	0	35
Slightly Warm	.	.	34-37	14	+1	24	+1	5	+1	9	+1	20	+1	23
Warm	28-32	9	>37	10	+2	24	+2	2	+2	10	+2	11	+2	21
Hot	32-38	2	.	.	+3	12	+3	2	+3	28	+3	7	+3	6
Very hot	38-42	0	.	.	.	.	.	.	.	.	+4	4	+4	2
Int. hot	>42	0	.	.	.	.	.	.	.	.	+5	11	+5	5

T: Thresholds for ET^* and SET are expressed in ($^{\circ}C$).

T: The ranges of each category for PMV , PMV_{ET^*} , PMV_{SET} , $DISC$ and $TSENS$ are expressed as ± 0.5 numerically.

%: percentage of time within the threshold.

Int: Intolerably

The resultant indices-output can be assessed against standard scales and thresholds, defined as:

- ET^* is based on six thresholds as described in ASHRAE Handbook of Fundamentals (2009) (Figure 18) and Auliciems, A. and Szokolay, S. (2007) (Figure 22).
- SET is based on five thresholds as described in Blazejczyk, K. et al. (2012) (Table 5).
- PMV is based on a 7-point scale, described in ISO 7730:2005.
- $DISC$ and $TSENS$ are based on an 11-point scale, described in Gagge, A. et al. (1986) Doherty, T. and Arens, E. (1988).

As shown in table 4.3, the three PMV indices have ranges which are greater than the standard $[-3$ to $+3]$. This might be due to the fact that all six input variables in the analysis are assumed to be independent of each other; also extreme values can be randomly selected in the same combination.

4.2.4 Uncertainty analysis

The indices' uncertainty refers to the error expressed by its variance and its nominal value. For a large number of iterations, the predicted output is likely to be normally distributed (Saltelli, A., Chan, K. and Scott, E., 2000). Thus the total uncertainty of the predictive model is expressed by estimation of the mean, the variance and the standard deviation (See Table 4.2). Under the rules set through this analysis, indices limit variations can be expressed as [$\text{'mean'} \pm \text{'standard deviation'}$], refer to Table 4.4. It is important to note that the PMV values are contained within the seven-point index set by ISO 7730:2005.

Table 4.4: Summary of indices uncertainty

	ET^*	SET	PMV	PMV_{ET^*}	PMV_{SET}	$DISC$	$TSENS$
Uncertainty	20.91	26.89	0.33	-3.17	-0.46	1.05	1.21
	± 5.51	± 8.49	± 2.58	± 3.13	± 4.05	± 1.43	± 1.72

4.2.5 Sensitivity analysis

The indices sensitivity to the six independent variables is shown in Table 4.5. These Pearson product moment correlation coefficients provide an insight of how the models' dependent variables respond to changes in the six independent variables.

These correlation coefficients (R) assess which independent variables have the most and the least influence on indices (Cohen, J., 1988). The obtained results are summarised as follows:

Table 4.5: Summary of correlation coefficients (R) between predictive indices and the six independent variables - environmental (EV) and personal (PV).

		<i>ET*</i>	<i>SET</i>	<i>PMV</i>	<i>PMV_{ET*}</i>	<i>PMV_{SET}</i>	<i>DISC</i>	<i>TSENS</i>
EV	<i>(T_a)</i>	0.68	0.32	0.34	0.55	0.30	0.41	0.30
	<i>(T_r)</i>	0.57	0.31	0.27	0.43	0.25	0.33	0.20
	<i>(RH)</i>	0.28	0.11	0.05	0.24	0.12	0.14	0.17
	<i>(V_a)</i>	-0.02	-0.05	-0.12	-0.17	-0.06	-0.03	-0.02
PV	<i>(M)</i>	-0.13	0.36	0.56	0.37	0.48	0.40	0.47
	<i>(I_{cl})</i>	-0.12	0.74	0.43	-0.02	0.67	0.62	0.67

- Ambient air temperature (T_a): shows a moderate influence on most indices, with the exception of ET^* and PMV_{ET^*} .
- Mean radiant temperature (T_r): shows a moderate influence on most indices, with the exception of ET^* and PMV_{ET^*} .
- Relative humidity (RH): with a correlation coefficient of (0.05), this variable has a negligible influence on PMV, and limited influence on the other indices with the exception of ET^* and PMV_{ET^*} .
- Air velocity (V_a): shows a very limited effect on all indices. Although of less significance, (V_a) has a negative correlation to all indices; the higher the air velocity, the lower the level comfort becomes.
- Metabolic rate (M): most indices appear very sensitive to (M), with the exception of ET^* and PMV_{ET^*} .
- Thermal insulation of clothing (I_{cl}): most indices appear very sensitive to (I_{cl}), with the exception of ET^* and PMV_{ET^*} .

In conclusion the models are more sensitive to ambient air temperature variation than to any of the other environmental variables. Also, based on the results of the sensitivity analysis, both personal variables, as metabolic rate (M) and thermal insulation of clothing (I_{cl}), are the most influential variables to most indices, with the exception of ET^* and PMV_{ET^*} . In particular, with regards to the two-node models, the sensitivity of the indices, seems to be divided into two groups. ET^* and PMV_{ET^*} are most sensitive to environmental variables; this association may be due to the fact that ET^* aims to combine the effects of temperature and humidity (Auliciems,

A. and Szokolay, S., 2007). On the other hand SET , PMV , PMV_{SET} , $DISC$ and $TSENS$ are mostly influenced by metabolic rate (M) and thermal insulation of clothing (I_{cl}). These results are surprising as different indices are most sensitive to different variables, yet they all aim to predict a person's level of thermal comfort.

4.2.6 Summary

As five of the seven indices are mostly influenced by personal variables, these should be assessed thoroughly, and determined with high accuracy. However (M) and (I_{cl}) are often given as constant values in comfort assessment and building energy simulation. For example, (I_{cl}) will be set at 0.5 clo during summer and 1 clo during winter Schiavon, S. and Lee, K. H. (2013). Concurrently, most field studies only estimate these two personal variables. With regard to (M), the protocols are described by Level 1: Screening or by Level 2: Observation in ISO 8996:2004. At most of Level 2 the accuracy of the results is estimated to be within $\pm 20\%$. Considering that the personal variables are the most influential variables within five indices, their high level of inaccuracy will undoubtedly undermine the results of the models. Consequently, it is critical to be able to determine those factors with high precision and accuracy.

In order to address this issue, wearable sensors may be able to provide a robust and durable approach to measure these variables. Monitoring systems should be designed to have minimum influence on the occupants while measuring each factor accurately. The following section presents a comprehensive exploration of methods used to measure each variables. This will contribute to the research design of the empirical studies in the choice of measuring methods and instruments.

4.3 Review of methods

This section provides a detailed description of the methodological framework by discussing which methods are most appropriate, given the aims and objectives set in the research design. Objective and subjective data collection methods are reviewed, focusing on the type of data gathered, on their practicalities, and on the approaches taken to data analysis. The review of current methods used to estimate activity level reveal some limitations in terms of accuracy and of usability in fieldwork. To address those issues, this section explores alternative methods to measure, to observe and to analyse people's activity level in households.

4.3.1 Thermal response time

With regards to the amplitude of the change in ambient temperature that participants may perceive, people are sensitive to small changes of temperature of 1°C to 2°C (Varges, G. and Stevenson, F., 2014). In this research, changes of 1°C in temperature will be analysed. Having defined the amplitude of the change in ambient temperature, the next step is to determine the time it may take participants to perceive a 1°C change in their environment. This may be defined as this research temporal unit of analysis. ASHRAE 55:2013 (5.3.5) define the limit on 1.1°C temperature drift, ramp and cyclic variations when not under the direct control of the participants as 15-minutes. However this only represents the limit before discomfort is perceived, and not the perception of change. As described by Hensel, H. (1981), the threshold condition for cold sensation is function of three parameters: (1) the temperature of the skin, (2) the rate and direction of temperature change, and (3) the area of stimulation. Following empirical evidence, the threshold of cold sensation by -1°C is perceived at a rate of change of $-0.04^{\circ}\text{C}\cdot\text{s}^{-1}$, or $-2.4^{\circ}\text{C}\cdot\text{min}^{-1}$ (Hensel, H., 1981) (pp. 20, Figure 3.1). While the results of study by Parkinson, T., de Dear R. and Candido, C. (2012) show that cold thermal sensation is perceived within 1 to 2 minutes when sedentary (Figure 3 and 4). In this research, the temporal unit of analysis was set at 1-minute.

4.3.2 Estimating activity level

4.3.2.1 Standard methods

Methods to estimate or to measure metabolic rate range from direct to indirect methods with associated levels of complexity and cost. ISO 8996:2004 provides a methodological framework composed of four levels, summarised below:

- Level 1, screening: Metabolic rate is estimated by reviewing the subject mean workload for a given occupation (level 1A) or for a given activity (level 1B). Each activity-intensity corresponds to a metabolic rate range, as follows: resting (55 to 70 W/m²), low level of

activity intensity (70 to 130 W/m²), moderate (130 to 200 W/m²), and high (200 to 260 W/m²). This estimation method only provides rough information and is associated with a great risk of error.

- Level 2, observation: Metabolic rate is estimated by observing the subject-working situation at a specific time. Information such as time and motion are required for this type of study, including body posture, type of work, body motion related to work speed. The accuracy of the results is estimated to be within $\pm 20\%$ (ISO 8996:2004, Table 1).
- Level 3, analysis: Metabolic rate is determined from the subject heart rate recordings over a representative period. This method uses an indirect determination, based on the relationship between oxygen uptake and heart rate under defined conditions. This method holds an accuracy of $\pm 10\%$ (ISO 8996:2004, Table 1).
- Level 4, expertise: Experts determine metabolic rate using three different methods: (1) oxygen consumption measured over short periods, (2) doubly labelled water (DWL) method over longer periods - 1 to 2 weeks, (3) direct calorimetry method in laboratory. Each one of these methods requires specific measurements, which undermine their application in field studies, over longer periods of time. These methods have an accuracy of $\pm 5\%$ (ISO 8996:2004, Table 1).

In summary, these four methods can be divided into subjective and objective. The subjective methods, as level 1 and 2 apply questionnaires, observations, diaries, and/or activity-logs. They are used in most studies, as at relatively low cost (de Dear, R., Brager, G. and Cooper, D., 1997) (Hunt, D. and Gidman, M., 1982) (Hong, S. et al., 2009). However these methods often provide a biased assessment and are associated with a great risk of error. This is an issue when incorporating their estimated results within predictive thermal comfort models, as metabolic rate has been proven to be the most influential variable for PMV and SET, as shown in the sensitivity analysis. High inaccuracy of metabolic rate estimation will undoubtedly undermine prediction of thermal comfort levels to design a new home or intervention strategies for reducing energy demand in homes. To overcome these limitations, objective methods in level 3 and 4 measure physiological mechanisms such as heart-rate, body temperature and metabolic effect. These provide a more reliable assessment of activity level, but their applicability in free-living environments may be limited. However with the recent advancements in more accessible, accurate and affordable sensing technologies, this may be overcome.

4.3.2.2 Heart rate monitoring

Over the past few years, sensing technologies have enabled the development of people's activity assessment (Trost, S., McIver, K. and Pate, R., 2005). One of the most noticeable has been the rapid uptake of heart-rate monitoring and accelerometry, which measures movement as biomechanical effect. Heart rate (HR) monitors have become more accessible and reliable in recent years as the demand for training tools in endurance sports increased (Achten, J. and Jeukendrup, A., 2003). To follow ISO 8996:2004 level-3 approaches, field studies may include the monitoring of HR to estimate energy expenditure (EE). As reviewed in this standard, HR levels show a significant relationship with oxygen uptake for heart rates above 120 beats per minutes (bpm) (Parsons, K., 2001). The estimation of metabolic heat production can be determined using HR counts as summarised in equation 4.5 (ISO 8996:2004):

$$HR = HR_0 + RM \times (M - BMR) \quad (4.1)$$

Where HR is the heart rate in bpm; HR_0 heart rate at rest under thermo-neutral conditions in bpm; RM is the increased in heart rate per unit of metabolic rate; M is the metabolic rate in W/m^2 ; and BMR is the basal metabolic rate in W/m^2 .

This equation has been developed in a set of equations (ISO 8996:2004, Annex C), where metabolic rate is estimated from heart rate recordings as a function of the subject's gender, age and weight. This method holds some limitations. At rest, small movements can increase a participant's heart rate, while the energy expenditure remains almost the same. Additionally, emotions could increase heart rate, while energy expenditure remains almost the same (Jeukendrup, A. and Gleeson, M., 2004). In those instances, other methods employed in this research, such as accelerometry and observation could support the evaluation of metabolic rate.

Instruments

In this research field study, two devices manufactured by Kalenji were used to monitor HR:

- Sensors and transmitter, Kalenji CW 300 coded; fitted in a chest strap belt, it records the heart electric activity using electrocardiography.
- Receiver and datalogger, Kalenji Cardio Connect; fitted in an independent device, it could be attached to the belt or kept in the participant's pocket.

This set of instruments was chosen as it was small, affordable, easily available if an additional set had to be replaced or purchased, and accredited for general use. Moreover participants did not need to wear a watch. As most participants were already wearing their own watch or

piece(s) of jewellery on their wrists, these items would have been removed during the monitoring study. Wearing another new item visible at all time, may have led to changes in behaviour, and compromise the results of the observation study. The Kalenji receiver and datalogger is a small button which would be kept in the participant's pocket.

During the study, continuous recordings, with a 2-seconds sensing interval, were taken. The datalogger memory capacity allowed over 35-hours of recording time, and was able to store information from multiple sessions. 35-hours capacity allows for 11 to 12-hours recording for 3-days. Data was transferred with the proprietary Geonaute software, and gathered as raw HR values in beats per minutes (bpm).

Analysis method

As the set of instruments chosen in this research is usually employed to monitor exercise, it was important to test how accurately it could monitor sedentary activity. As part of an MSc workshop, four tests were carried out in climate chamber in October 2014. Temperature was set at 21 °C, and relative humidity at 50 %. Participants were wearing similar clothing levels, around 1 clo. A preparatory period lasted about 10 minutes, and took place just outside the climate chamber. This served two functions: firstly, to ensure all participants were adapted to a similar temperature before the experiment; and secondly, to ensure they had been sitting still for about 10 minutes in order to achieve a similar level of pre-experiment metabolic activity. During each test, a group of four participants varying in gender, age (22 to 35 years old) and weight (50 to 90 kg) were asked to perform an activity for 30-minutes, described as follows:

- Group 1: sitting watching a movie.
- Group 2: standing.
- Group 3: light exercise (yoga video).
- Group 4: intense exercise (exercise video).

The results were analysed using ISO 8996:2004 level-3 approach, and showed that the Kalenji devices are relatively accurate. Group 1 and 2 had low level of metabolic rate varying from 74.5 to 90.8 W/m² or 1.3 to 1.6 met; Group 3 had high level of metabolic rate varying from 209.8 to 265.6 W/m² or 3.6 to 4.6 met; finally Group 4 had very high level of metabolic rate varying from 312.1 to 408.2 W/m² or 5.4 to 7 met.

In the research output from the HR monitor was analysed with ISO 8996:2004 level-3 approach, and the associated set of equations to estimate metabolic rate. These equations are

function of the participants' gender, age and weight. Finally, results were averaged over one minute epochs.

Application to the research

In the field study, 20-participants' heart rate was monitored for a minimum period of 3-days. This enabled metabolic rate to be ascertained as objective, quantitative and continuous data. The results were compared and contrasted to the accelerometer recordings and observations of the SenseCam's visual diary to assess the validity of the output. Using the five activity classifications described in ISO 8996:2004 - Table A.2, three instances of resting, low, moderate, high and very high metabolic rate were selected randomly from the monitoring log for each participant. Then the associated pictures were reviewed. Although the results were conclusive for the selected sequences, this may not always be the case. Variations in heart rate may be caused by variation in metabolic rate but also by other factors such as emotions. For example, heart rate may increase as a response to psychological factors such as stress. This will introduce bias in the estimation of activity level. To answer this limitation, cross validation was carried out using a second method of estimation described in the next section.

4.3.2.3 Motion sensors - Accelerometry

In light of the results of the sensitivity analysis, participants' activity level is the most influential variable in the standard predictive thermal comfort models. Therefore this research aims to monitor this variable with greater accuracy than current estimation methods. To estimate energy expenditure, accelerometers quantify activity level by measuring acceleration of a person's movement. Acceleration is defined as the change in speed over time, it is expressed in units of gravitational acceleration (g), with $1\ g = 9.8\ m/s^2$. It is influenced by the frequency, the duration and the intensity of the body movement. If the acceleration value is equal to zero, then the subject might be static or has a constant speed (Chen, K. and Bassett, D., 2005). When a body is in movement, then energy expenditure is related to the acceleration of the body mass (BM). Therefore accelerometry is one of the most recent methods to monitor a person's activity level. As small portable devices, accelerometers are of two types; piezoelectric or piezoresistive sensors (Bonomi, A., 2011).

The first type, piezoelectric accelerometers consist of a piezoelectric element with a seismic mass. When acceleration occurs, the mass causes the piezoelectric element to bend, which displaces a charge to build-up on one side of the sensor. This results in variation in the output voltage signal (Godfrey, A. et al., 2008). To measure acceleration in three axes, several unidirectional sensors are assembled into one instrument (Bouten, C. et al., 1997). These accelerometers

are relatively small and lightweight. Their outputs are the amplitude and the frequency of acceleration signals; these are rectified and integrated in a time interval to determine the 'activity counts' (Bouten, C. et al., 1997). An 'activity count' is an arbitrary unit varying across devices (Rothney, M. et al., 2008).

The second type of device, piezoresistive accelerometer consists of polysilicon structures with springs (Bao, M-H., 2000). As the human body accelerates, it causes displacement of the silicon structure, resulting in a change in capacitance. This change is processed into an analogue output voltage, which is proportional to the acceleration. The outputs are raw acceleration signals, which are often analysed using recognition techniques to identify different types of activity.

The main limitation of accelerometry lies with its underestimation of metabolic rate due to the confounding effect of several factors, including temperature (Jeukendrup, A. and Gleeson, M., 2004). For example, if a participant was to stay seated in a cold room, the accelerometer will indicate low level of energy expenditure, which might be misleading. As shown in the literature review, the human body response to cold will be an increase in metabolic rate to keep the core temperature constant. Other methods such as heart-rate monitoring or observation may complement the use of accelerometry, and support the evaluation of metabolic rate.

Table 4.6: Accelerometer performance specification

Parameters	KXP84
Range	$\pm 2g$
Sensitivity	$819 \text{ counts/g} \pm 25$
Resolution	$1.22mg$
Power supply	$3.3V$
Operating temperature	$-40 \text{ to } +85^{\circ}\text{C}$

Instrument

The accelerometer used in this research is one of the sensors housed in the SenseCam (Vicon Motion Systems, Microsoft, UK) (Hodges, S. et al., 2006). It comprises of a tri-axial piezoresistive accelerometer, Kionix KXP84 (Refer to Table 4.6). This instrument captures body movement in three orthogonal directions. The raw acceleration signal was sampled and stored on a SD card within the SenseCam and later transferred to a computer for analysis. The device was chosen as it was lightweight (of a similar size to a badge), affordable, and accredited for general

use. More importantly it was the only commercially available device at the time of the study, which incorporated the array of sensors need for the research and a camera.

The participants worn the device on the chest, thus the body core acceleration was monitored, allowing activities such as laying, sitting, standing, walking, running and going up/down to be identified directly from the accelerometer's readings. This is an important feature of the SenseCam as most commercially available devices monitor acceleration at the wrist, for example the FuelBand by Nike, the Up by Jawbone, the Flex by Fitbit, and the GT9X Link by ActiGraph. This sensor's location introduces bias as it is assumed that each activity is associated with a specific wrist movement (Patterson, S. et al., 1993).

The SenseCam was worn on the chest on a cord around the neck. Although it records the body's core acceleration, the device itself may move when activity occurs. Therefore the acceleration recorded may have been from the participant's movement and from the movement of the device. To address this issue, a participant executed a sequence of activities twice, first with the SenseCam worn on a cord around the neck, and then clipped to a jumper at the same location on the chest. When walking or going up/down, the total acceleration generated by the movement of the device was estimated as lower than 0.01g. Applying a correction factor was considered too unreliable, as different activities and participants will require different correction factors. This remains a limitation of the method applied in the research. Future studies may provide a clip to the SenseCam, so it can be secured to pockets or belts, or attached directly to clothing.

Analysis method

Accelerometer output was derived from raw acceleration signals, followed by the calculation of the vector magnitude, movement intensity. Combining the signals of the three axes makes the movement intensity value insensitive to orientation of the accelerometer with regards to the body.

Participants' total acceleration (TA) was calculated as the normalized magnitude of the acceleration vector including the earth's gravity; see equation 4.2 (Shala, U. and Rodriguez, A., 2011). Then the linear acceleration (LA) was estimated as the difference between TA and the acceleration due to Earth's gravity; see equation 4.3.

$$TA = \sqrt{x^2 + y^2 + z^2} = LA + g \quad (4.2)$$

$$LA = \sqrt{x^2 + y^2 + z^2} - g \quad (4.3)$$

Where TA is the total acceleration in m/s^2 , LA is the linear acceleration in m/s^2 , x is acceleration in the x-axis in m/s^2 , y is acceleration in the y-axis in m/s^2 , z is acceleration in the z-axis in m/s^2 , and g is the acceleration due to Earth's gravity of 9.81 m/s^2 .

To determine activity level from motion sensors, most analysis methods are based on controlled experiments in laboratories, often using indirect calorimetry or the doubly labelled water techniques. The accelerometer's outputs are compared to the results of physiological metabolic rate measurements. Combining these two sets of results, regression analyses are carried out to determine activity level from the accelerometer readings (Bouten, C. et al., 1996) (Chen, K. and Sun, M., 1997) (Freedson, P., Melanson, E. and Sirard, J., 1998). Validation studies have reported correlation values from 0.58 to 0.92 (Chen, K. and Bassett, D., 2005). It should be noted that most of the studies have associated 'activity counts' rather than gravitational values (g) with energy expenditure. 'Activity counts' are difficult to interpret as each device has proprietary data processing methods and assumptions. The device used in this study gives raw accelerometry values expressed in (g), which are easier to interpret. However only a limited number of studies have reviewed the outputs of piezoresistive accelerometers (van Hees, V. et al., 2011). Calibration could be completed through experimental study, from which a traditional regression model could be derived, or through more advance processing approaches, such as activity pattern recognition (Godfrey, A. et al., 2008). For example, patterns in the accelerometer's output signals can be recognised with an activity detection algorithm. These can detect types of activity, for example: lying, sitting, standing and walking (van Hees, V., van Lummel, R. and Westerterp, K., 2009). Combined these results with controlled experiments in laboratory; estimation of energy expenditure can be even more accurate (Gyllenstein, I. and Bonomi, A., 2010).

As in this study, accelerometry values were expressed in (g) and the linear acceleration (LA) was integrated over a 1-second interval to estimate participants' speed. The results were then averaged over the each 1-minute epoch. Assuming that participants walked between locations in their home Ralston's equation (1958) may be applied; see equation 4.4.

$$E_w = 29 + 0.0053v^2 \quad (4.4)$$

Where E_w is the energy expenditure in cal/min/kg , and v is velocity in m/min .

After converting the variables in the Ralston's equation to SI units, power was calculated and divided by the participants' body surface area to estimate metabolic rate (M) in W/m^2 and

then in met; where $1 \text{ met} = 58.2 \text{ W/m}^2$ (ISO 7730:2005). Participants' body surface area were calculated using Du Bois formula (ISO 8996:2004, 7.1.2), with participants' body weight and height drawn from the questionnaires survey. This estimation does not take into account the energy required to sit, or to climb/descend stairs; such activities may be incorporated in future analysis (Rassia, S., Hay, S., Beresford, A. and Baker, N., 2009). For example, to detect these vertical movements an altimeter or barometric pressure sensor may be fitted to the wearable sensor-kit.

Application to the research

In this research, the SenseCam was worn concurrently to the heart-rate monitor enabling the evaluation of participant's metabolic rate as objective, quantitative and continuous data. Results were validated using the output from the SenseCam's visual diary. Similar validation checks as the heart rate method were undertaken using the five activity classifications described in ISO 8996:2004 - Table A.2. The results were also conclusive as each classification was estimated within the ranges of ISO 8996:2004. Furthermore, as described in Gauthier, S. and Shipworth, D. (2013), activity level was estimated as two time series using the heart rate monitoring and accelerometer output. The visual diary provided an explanation to the discrepancy between both estimations, and validated the final results.

4.3.3 Estimating clothing level

With regards to determining thermal insulation of clothing, the methods described in ISO 9920:2009 may be followed. The clothing insulation level is estimated for a given combination of garments, or the sum of individual garments, from reference tables in ISO 9920:2009. Although prone to observation bias, this is the most commonly used method in the field studies (de Dear, R., Brager, G. and Cooper, D., 1997) (Hunt, D. and Gidman, M., 1982) (Oseland, N. and Raw, G., 1991) (Hong, S. et al., 2009). Emerging methods include the use of infrared cameras (Yu, S., Tan, D. and Tan, T., 2006) (Revel, G., Sabbatini, E. and Arnesano, M., 2012), and wearable sensors measuring the temperature gradient between the inner and outer layer of clothing. The later method was use in this study using the SenseCam's sensors and datalogger (Vicon Motion Systems, Microsoft, UK).

Instruments

The SenseCam incorporates a temperature sensor (Nat Semi LM75), a light intensity sensor (TAOS TCS230), a passive infrared detector (Seiko SKP-MS401), a tri-axis accelerometer (Kionix KXP84) and a magnetometer (Hodges, S. et al., 2006). Calibration tests were carried out in climate chamber prior to the studies; results showed that for the temperature sensor,

the measurement error was within the sensor's accuracy range (± 2 °C). The Nat Semi LM75 is defined as an integrated circuit (IC) temperature sensors, which uses a small transducer to convert temperature input into a proportional current output. Its main advantages is to be small, inexpensive, and can easily be integrated into existing systems. However the Nat Semi LM75 output is not within the ISO 7726:2001 required accuracy of ± 0.5 °C for air temperature. As no other instrument was available at the time of the study which combined the range of sensors required, the SenseCam was chosen as the wearable monitoring instrument for the research. The SenseCam also provided a visual diary of participants whereabouts in their home and a record of measurements taken by each sensor.

Analysis method

In this study, the participants thermal insulation of the clothing (I_{cl}) was estimated using the ASHRAE 55:2013 - Appendix B as a preliminary estimate of the surface temperature of clothing (Equation 4.5 and 4.6). For this to apply two conditions should be met: (1) the mean air velocity should be equal to, or lower than, 0.1m/s, and (2) participants should be sedentary.

$$T_{clo}^a = T_a^a + \frac{(35.5 + T_a)}{(3.5 \times (6.45 \times I_{cl} + 0.1))} \quad (4.5)$$

$$I_{cl} = [([(35.5 - T_a) \div (T_{clo}^a - T_a^a)] \div 3.5) - 0.1] \div 6.45 \quad (4.6)$$

where T_{clo}^a is the surface temperature of clothing in Kelvin, T_a^a is ambient air temperature in Kelvin, T_a is ambient air temperature in Celsius, I_{cl} is thermal insulation of clothing in m^2K/W . (note $0.155 m^2K/W = 1clo$, ISO 7730:2005).

Having determined the method of estimation, each term of the equation was estimated as follows. First, ambient air temperature (T_a) was measured using HOBO U12-012, these are integrated sensor/datalogger type. The sensor are also integrated circuit (IC) temperature sensors. Calibration tests were carried out in climate chamber prior to the studies; results show that the measurement errors were within the sensors accuracy range (± 0.35 °C), and within the ISO 7726:2001 required accuracy of ± 0.5 °C for air temperature. Three sets of 4-dataloggers were placed in living-rooms and in bedrooms, fastened to wooden-poles, and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground, to comply with the requirements set by ISO 7726:2001. For the purpose of the analysis, T_a represents the temperature monitored in living room while standing calculated as the mean temperature over three heights: 0.1m; 0.6m; and 1.7m. As the monitoring frequency was set at 5-minutes, the data were re-sampled to a 1-minute

sampling rate, with each 1-minute data-point taking on the value of the nearest 5-minute data-point.

Relative air velocity (v_a) was measured during the home visit with a calibrated hot-wire anemometer (Testo 425). For all participants, the results were equal to or below 0.1m/s. As the study was carried out in winter, a relative air velocity of 0.1m/s was assumed for all cases on a basis that openings, such as windows, tend to remain closed (Hong, S. et al., 2009).

Finally, the surface temperature of clothing (T_{clo}) was estimated using the SenseCam's temperature sensor, worn on the participants' chest. First, readings were averaged over the chosen temporal unit of analysis of 1-minute. Then a normalising process was carried out, including:

- Identifying and discounting the time taken for the SenseCam to reach thermal equilibrium with its environment. This is a function of the observed thermal resistance and initial temperature of the SenseCam when switched-on and worn. To estimate this temperature rise-time, a calibration study was undertaken, and concluded that the response time of the device was around 5-minutes, and it takes on average 22-minutes to reach equilibrium when first worn.
- To fulfil the second condition of the equation, it was necessary to identify when participants were sedentary and to discount T_{clo} values when participants were in motion. To do this, the mean linear acceleration (LA) over the 1-minute epoch was estimated using the tri-axis accelerometer recordings, and compared to the images of the visual diary. Results show that participants were sedentary when the measured mean linear acceleration over 1-minute was within the range: $-0.075\ g$ to $+0.075\ g$ or $-0.735\ m/s^2$ to $+0.735\ m/s^2$. Based on this observation, a data filter was written that identified T_{clo} when sedentary.
- Identifying and discounting other artefacts, including the SenseCam been taken-off but left switched on, and SenseCam been worn under an item of clothing. The first of these was identified by using the accelerometer recordings, i.e. if $-0.01\ g < LA < +0.01\ g$ then T_{clo} was discounted. The second was identified by using the light sensor data (CLR). The efficacy of both filters were established by comparing the respective sensor data to the visual diary output.

As the monitoring was carried-out on the chest, only the upper-body thermal insulation level was measured. Lower body thermal insulation was taken as a constant value of $0.3\ clo$ based on the aggregation of lower body garments including underwear, trousers or skirt, and socks. This was added to the final I_{cl} value (ISO 9920:2009).

Application to the research

Wearable sensors were employed in the study to estimate clothing insulation as objective, quantitative and continuous data. Results were then used to ascertain the frequency of change in participants clothing level and the probability of this action to alleviate cold thermal discomfort. Limitations of this methods lays mainly in the chosen assumptions, analysis method, and interpretation of the results.

As the SenseCam was worn on a cord around the neck, the temperature sensor was not in direct contact with the outer layer of the garment. Although the participants were sedentary, this may have introduce some measurement error. Furthermore the study only recorded temperature at the chest, therefore an assumption was made for the lower body garment(s). This may have introduce further bias.

The analysis method relies an equation from ASHRAE 55:2013 standard. Further studies may test this estimation method by carrying out experiments in controlled environment. For example, participants may be asked to were different garments under different hygrothermal conditions.

The ambient air temperature was assumed to be the temperature in living room while standing. This may have introduce further bias, as participants may have been in different location within their home, and in different position. Unfortunately the research had access to a limited amount of environmental sensors, therefore only two rooms were monitored, the living room and the bedroom. The temperature in living room was chosen as the results of the visual diary analysis showed that participants tend to be located more frequently in living room rather than bedroom. With regards to the chosen body position, the estimation for standing is over 1.6m (from 0.1 to 1.7m) while for seating it is over 1m (from 0.1 to 1.1m) (ISO 7726:2001, Table 5); therefore estimation of temperature for the standing position was considered more representative of the indoor conditions.

Finally, to address part of these limitations, results were validated using the output from a visual diary. As the SenseCam's camera has a 119 wide-angle lens (Hodges, S. et al., 2006), the pictures from the visual diary showed if a participant was wearing a short-sleeve top, a jumper or using a blanket. For each participants, pictures from the visual diary were reviewed to validate the initial clothing level at the beginning of each day. Then for the rest of the day changes in T_{clo} were assessed; if T_{clo} increased or decreased by 1 °C or more, associated pictures were identified at the time of the change and 5-minutes prior and posterior to this change. This analysis enabled the validation of changes in clothing level.

4.4 Empirical study results and analysis

To follow from the review of methods to estimate activity and clothing levels, this study introduces a mixed-method framework drawn from psychological and physiological studies. Automated visual diaries with wearable sensors (including: tri-axis accelerometers, heart-rate monitors, light intensity sensor, and temperature sensors) provided measured input from which metabolic rate and thermal insulation of clothing were ascertained over a continuous period of time. The wearable sensors included:

- A SenseCam manufactured by Vicon Motion Systems (Microsoft, UK). It comprises of a tri-axial piezoresistive accelerometer (Kionix KXP84), a light intensity sensor (TAOS TCS230), and a temperature sensors (Nat Semi LM75).
- Heart-rate monitors manufactured by Kalenji - Sensors and transmitter (Kalenji CW 300 coded), and Receiver and datalogger (Kalenji Cardio Connect).

This mixed-method approach was applied to 20-participants living in 19-different dwellings over a minimum period of 10-consecutive days, in the South-East of England during the winters of 2012 and 2013. Concurrently, environmental variables were recorded. The sampling frame was defined by the 3-physiological attributes prescribed by ISO 8996:2004, Annex C, as gender, age and weight. The sample frame was populated across combinations of categories using a mixture of convenience and snowball sampling.

The aim for this study was to develop methods to estimate metabolic rate and clothing insulation values as objective, quantitative and continuous data. Following on, the results from mixed-method framework allowed empirical probability distributions to be generated. Although this study sample size is relatively small, it allows to develop a method which may be applied to larger studies. Then their results may be used as input in building energy simulation modelling.

4.4.1 Estimating activity level using heart rate monitors

Applying the methods described in the last section, the monitoring study was able to estimate participants' activity levels from heart rate monitoring. When processing the data, about 17% of the recordings were outside the bound of the level stated in ISO 8996:2004 Table B.3. The lower bound was taken as 40 W/m^2 for '*sleeping*', and the higher bound was taken as 300 W/m^2 for '*walking uphill, even path, solid, without load, 25 inclination, 3 km/h*', which is assumed to be equivalent to climbing stairs. These identified outliers might be due to measurement errors, for example the chest-strap might not have been fitted correctly, or there might have been interferences in the signal between the transmitter and the receiver. The analysis found

that the estimated mean metabolic rate value for the entire dataset was 1.58 ± 1.16 met, while the estimated mean metabolic rate value for the dataset without outliers was 1.69 ± 0.74 met. After a review of the visual diary, the following analysis was based on the dataset without outliers.

Figure 4.2: Density distribution of estimated metabolic rate for all participants, and activity level value of 1.2 met prescribed by EN 15251:2007 (Table A.2) for residential building in living spaces.

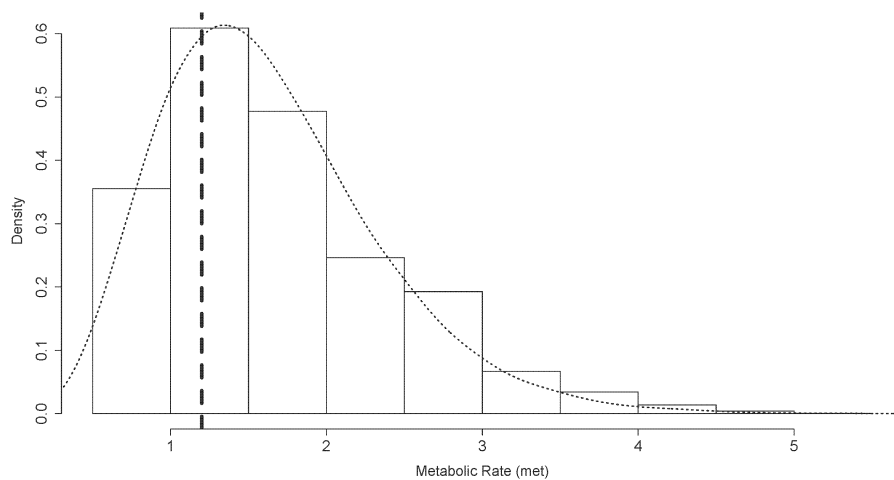
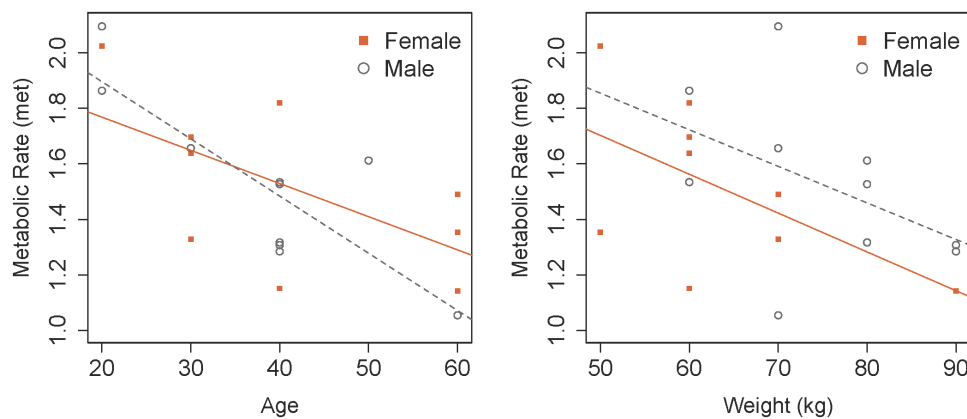


Table 4.7: Summary of the statistical characteristics of estimated metabolic rate from heart rate monitors for all participants.

Sample	Sample size (no. of observations)	12,315
Central Tendency	Mean	1.69
	Median	1.53
	Mode	1.30
Spread	Variance	0.55
	Standard deviation	0.74
	Maximum	5.14
	Minimum	0.69
	Range	4.45
	Quantile (.75)	1.12
	Quantile (.25)	2.09
Gamma distribution	Shape	5.71
	Rate	3.38

The resultant metabolic rate values are summarised in Figure 4.2 and Table 4.7, with an indicative gamma-distribution inferred from the histogram. The mean value of 1.69 met is higher than the activity level value of 1.2 met prescribed by EN 15251:2007 (Table A.2) for residential building living spaces. As the dataset is right-skewed, the median might be a better central tendency estimate. In this case the median is equal to 1.53 met, which is still higher than the standard value, and higher than findings in literature (Hunt, D. and Gidman, M., 1982) (Hong, S. et al., 2009).

Figure 4.3: (Mean activity level) and (Age), followed by (Mean activity level) and (Weight) with the fitted linear regression lines for each (Gender).



The following analysis reviews the influence of the three sample frame criteria (gender, age and weight) on activity level, and compares and contrasts the results against the study carried out by Hunt, D. and Gidman, M. (1982). On average, male participants in this study were slightly more active than female participants, which is the opposite of Hunt's findings (1982). Mean metabolic rate was 1.72 ± 0.73 met for men, and 1.67 ± 0.75 met for women, which is higher than Hunt's results, by 0.28 met for women and 0.54 met for men. Also there was found to be a significant difference between the two groups (Wilcoxon signed-rank test, p -value < 0.05). Activity levels seemed to be higher for younger participants and for participants with lower weight, see Figure 4.3. The linear correlation coefficients between mean activity level and participant's age was -0.83 for men, and -0.61 for women. The linear correlation coefficients between mean activity level and participant's weight was -0.47 for men and -0.57 for women.

In summary the estimation of activity level from heart rate followed the Level-3 approach described in ISO 8996:2004, yet the results are much higher than previous studies' estimations.

Also 17% of the data was considered 'out of range', attributed mainly to measurement errors. Moreover the monitoring was only carried out for a maximum period of 3-days due to the memory capacity of the logger. To address some of these issues the following section will review the results of the accelerometer monitoring.

4.4.2 Estimating activity level using accelerometers

Following the methods described in the last section, the monitoring study was able to estimate participants' activity levels using accelerometry. The resultant metabolic rate values are summarised in Figure 4.4 and Table 4.8, with an indicative gamma-distribution inferred from the histogram. The estimated range of 1.11 to 2.12 met is within the expected standard range of 0.8 to 4 met, as described in ISO 7730:2005 (section 4.1). However the mean value of 1.32 met is higher than the value of 1.2 met prescribed by EN 15251:2007 (Table A.2) for residential buildings in living spaces. Referring to previous studies' estimations, a mean of 1.32 ± 0.13 met is very close to Hong's results of 1.35 ± 0.18 met (2009), and Hunt's results of 1.19 ± 0.50 met for men and 1.39 ± 0.55 met for women (1982).

Figure 4.4: Density distribution of estimated metabolic rate for all participants, and activity level value of 1.2 met prescribed by EN 15251:2007 (Table A.2) for residential building in living spaces

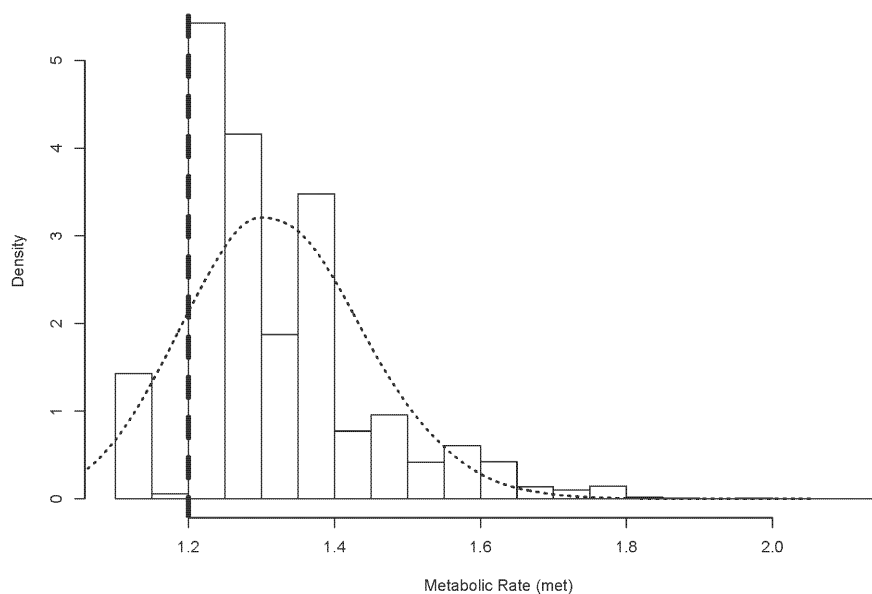


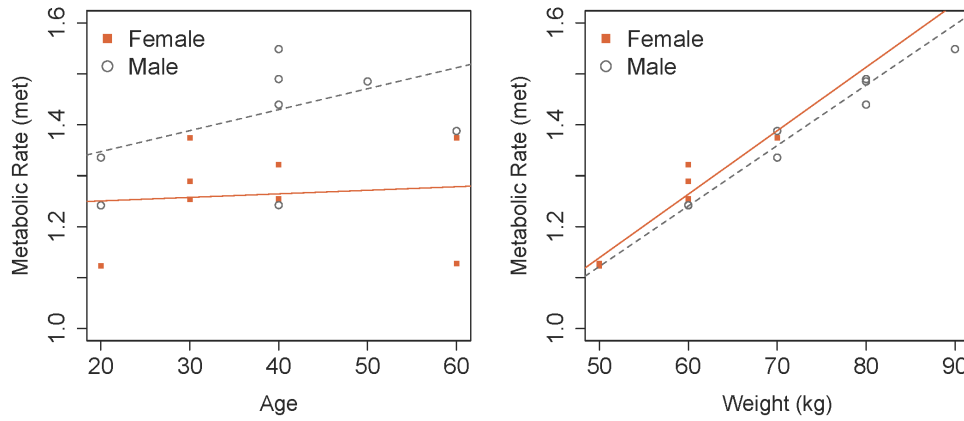
Table 4.8: Summary of the statistical characteristics of estimated metabolic rate from accelerometers for all participants

Sample	Sample size (no. of observations)	31,444
Central Tendency	Mean	1.32
	Median	1.28
	Mode	1.13
Spread	Variance	0.02
	Standard deviation	0.13
	Maximum	2.12
	Minimum	1.11
	Range	1.01
	Quantile (.75)	1.37
	Quantile (.25)	1.24
Gamma distribution	Shape	116.79
	Rate	88.49

A similar analysis to that carried out on the estimation of activity level from heart rate monitoring, was performed to investigate relationships between activity level and the three sample frame criteria (gender, age and weight). On average male participants were slightly more active than female participants, this is a similar result to the findings with heart rate monitoring. Mean metabolic rate was 1.39 ± 0.17 met for men, and 1.28 ± 0.09 met for women, which is higher than Hunt's results for men ($+0.21$ met), but lower for women (-0.11 met). Also there was found to be a significant difference between the two groups (Wilcoxon signed-rank test, p -value < 0.05).

As shown in Figure 4.5, there was a very weak relationship between activity level and age, however the activity level seemed to have a very strong relationship with weight. The linear correlation coefficients between mean activity level and participant's age was 0.38 for men, and 0.1 for women. The linear correlation coefficients between mean activity level and participant's weight were 0.96 for men and 0.97 for women. Interestingly these results are very different to the results found within heart rate monitoring. This may be due to the fact that participants wore the accelerometers for much longer periods of time - minimum 10 days monitoring period for each participant. Also the accelerometer was part of the SenseCam and worn around the neck, whereas the heart rate sensor was worn tight to the chest, which might have restricted movement. This shows the importance of cross validation in such a monitoring study.

Figure 4.5: (Mean activity level) and (Age), followed by (Mean activity level) and (Weight) with the fitted linear regression lines for each (Gender).



4.4.3 Estimating clothing level

Following the methods described in the the last section, the monitoring study estimated participants' mean clothing level as 0.82 ± 0.20 clo. The resultant clothing insulation values are summarised in Figure 4.6 and 4.9, with an indicative gamma-distribution inferred from the histogram. The estimated range of 0.43 to 1.99 clo is within the expected standard values as described in ISO 7730:2005 (section 4.1) as 0 to 2 clo. However the mean value of 0.82 clo is lower than the assumed winter value of 1 clo given as constant in building energy simulations (Schiavon, S. and Lee, K. H., 2013), and the minimum clothing level for winter of 1 clo prescribed by EN 15251:2007 (Table A.2). Yet, previous monitoring studies show similar findings; Hunt estimated 0.86 ± 0.19 clo for men and 0.81 ± 0.16 clo for women (1982), while Hong estimated 0.82 clo pre-retrofit and 0.75 clo post-retrofit (2009).

The role of the three sample frame criteria (gender, age and weight) on participants' clothing levels was then reviewed. On average women wore warmer clothing ensembles than men; this is the opposite to the findings by Hunt, D. and Gidman, M. (1982). Mean thermal insulation of clothing was 0.78 ± 0.17 clo for men, and 0.85 ± 0.25 clo for woman. This is a decrease of 0.08 clo for men, and an increase of 0.04 clo for women from Hunt's results (1982). Also there was found to be a significant difference between the two groups (Wilcoxon signed-rank test, p -value < 0.05).

Figure 4.6: Density distribution of estimated thermal insulation of clothing for all participants and minimum clothing level for winter of 1 clo prescribed by EN 15251:2007 (Table A.2)

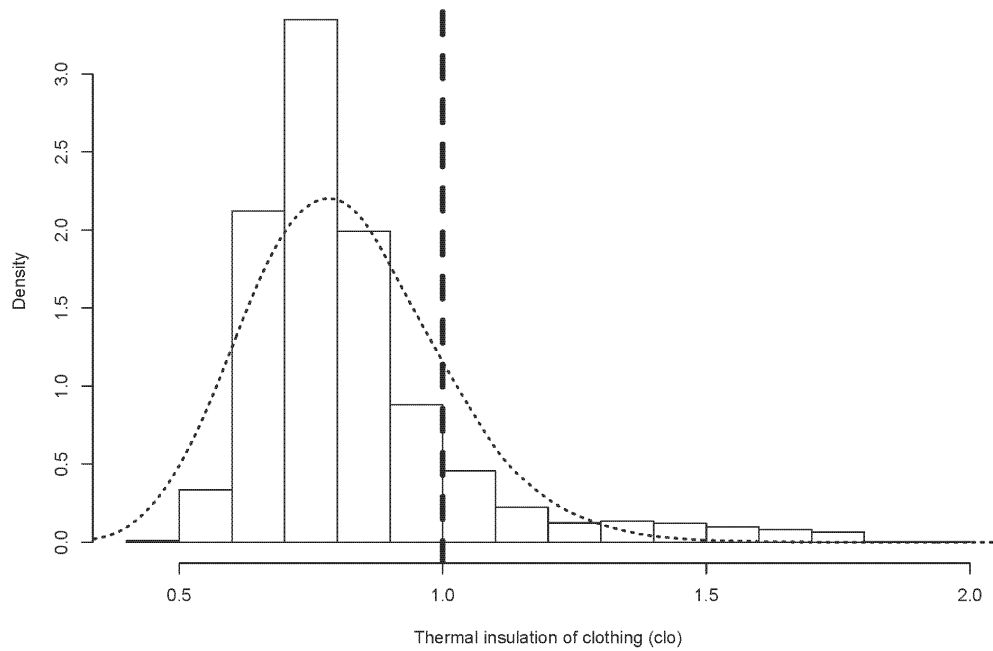
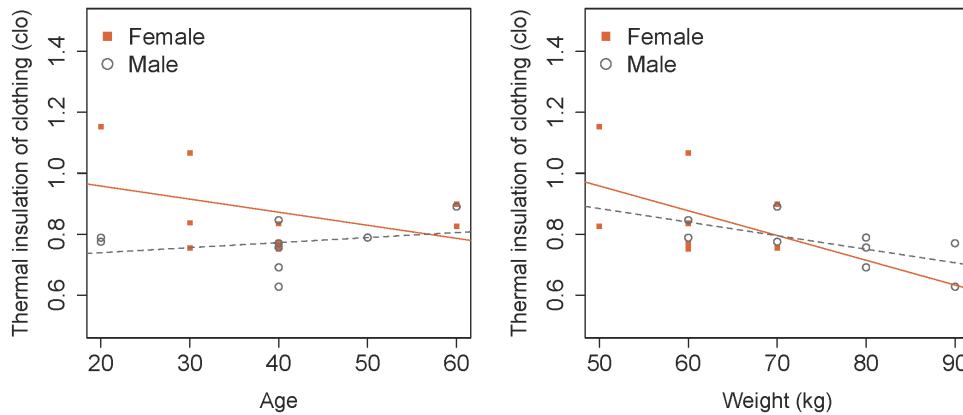


Table 4.9: Summary of the statistical characteristics of estimated thermal insulation of clothing for all participants

Sample	Sample size (no. of observations)	18,559
Central Tendency	Mean	0.82
	Median	0.77
	Mode	0.77
Spread	Variance	0.04
	Standard deviation	0.20
	Maximum	1.99
	Minimum	0.43
	Range	1.56
	Quantile (.75)	0.86
	Quantile (.25)	0.69
Gamma distribution	Shape	19.92
	Rate	24.42

Figure 4.7 shows a weak relationship between participants mean clothing level and age. The linear correlation coefficients between mean clothing level and participant's age was 0.27 for men, and -0.41 for women. Women tend to wear less warm clothing as they are older, and the opposite for men. Now reviewing the relationship between mean clothing level and weight. Both genders tend to wear warmer clothing as they weigh less. The linear correlation coefficients between mean clothing level and participant's weight were -0.65 for men, and -0.41 for women.

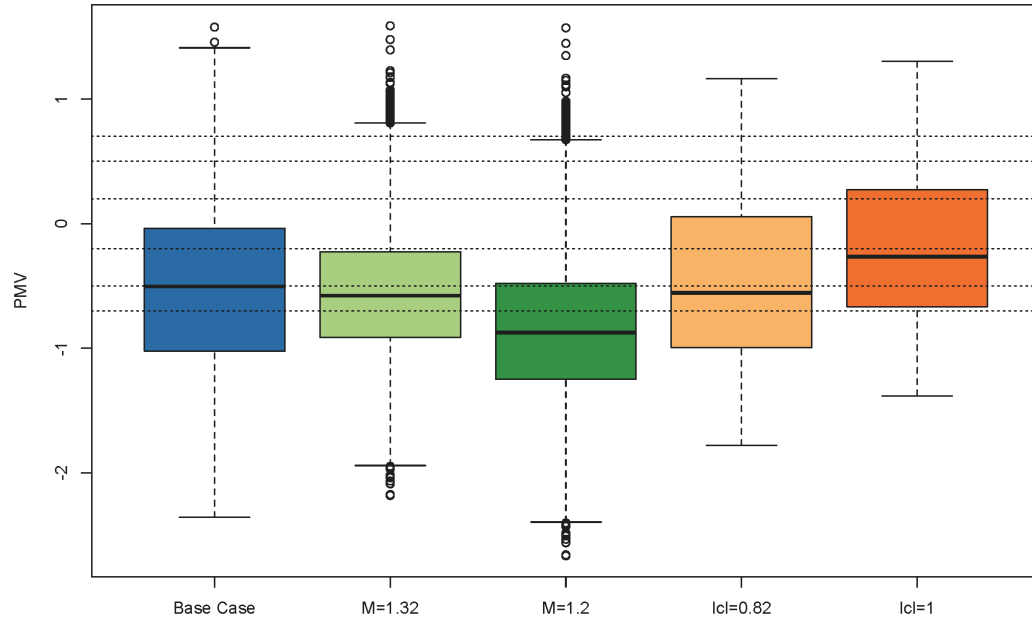
Figure 4.7: (Mean clothing level) and (Age), followed by (Mean clothing level) and (Weight) with the fitted linear regression lines for each (Gender).



4.4.4 Summary

This mixed-methods approach allows for activity (M) and clothing (I_{cl}) levels to be determined as objective, quantitative, and continuous data. In addition, results from this experimental investigation generated probability distributions for the levels of M and I_{cl} in residential settings during the winter season. Surprisingly, the mean I_{cl} level was 0.82 clo, which is lower than the 1 clo prescribed by EN 15251:2007. On the other hand, measured mean M was 1.32 met, which is higher than the 1.2 met also prescribed by EN 15251:2007. In summary the standard M and I_{cl} values differ from the measured values, although both are within the standard deviation of the mean as 1 clo is within 0.82 ± 0.2 clo and 1.2 met is within 1.32 ± 0.13 met. However as M and I_{cl} are the most influential variables in the PMV and SET models, these observed differences from the standard values may have a great effect on output PMV as shown in Figure 4.8.

Figure 4.8: Distributions of PMV output for 5-scenarios: (1) Base Case: input from the study for M and I_{cl} (Sample size number of observations: 17,892), (2) Input from the study for I_{cl} and $M=1.32\text{met}$, (3) Input from the study for I_{cl} and $M=1.2\text{met}$, (4) Input from the study for M and $I_{cl}=0.82\text{clo}$, and (5) Input from the study for M and $I_{cl}=1\text{clo}$. (Note: thresholds PMV for categories A, B and C shown in dotted lines, ISO 7730:2005 Table A.1).



Using the empirical study monitoring results as input, different scenarios were tested. The results illustrated in Figure 4.8 show that a reduction in I_{cl} from 1 to 0.82 clo reduces the mean PMV from -0.23 to -0.51; which is then outside the bound of category B acceptability of ISO 7730:2005. In parallel, an increase in M from 1.2 to 1.32 met increases the mean PMV from -0.87 to -0.57; which is still outside the bound of category B but inside the bound of category C of ISO 7730:2005. Moreover, there is a significant statistical difference in means between the two M scenarios ($M=1.2$ and $M=1.32$), and also between the two I_{cl} scenarios ($I_{cl}=1$ and $I_{cl}=0.82$) (Wilcoxon signed-rank test, $p\text{-value} < 0.05$).

In conclusion, using empirical and more informed input in the PMV model and building energy simulation may have great effect on the assessment of buildings. Despite the important number of observations, 31,444 for M and 18,559 for I_{cl} , the number of participants in this research was relatively small; therefore the results may be strengthened by further studies adopting the same method in different seasons and regions.

4.5 Summary

In summary the I_{cl} value in winter was 0.18 clo lower than the assumed typical value. This low clothing level may partially be compensated by higher observed metabolic rate. When combining these results with the environmental monitoring, the predicted mean votes are substantially below those expected in the standard model, with observed values of -0.54 ± 0.65 PMV score. This suggests that occupants may be engaging in other adaptive behaviours, not currently accounted for within the standard model. The following chapter will be developing method to identify these adaptive behaviours.

Chapter 5

Monitoring people cold thermal discomfort responses

5.1 Outline

As highlighted in the last chapter, occupants maybe engaging in behaviours not accounted for in the current models. These may emanate from psychological or behavioural adaptation mechanisms as underlined in the literature review. To explore these mechanisms, this chapter will first review methods to capture people's cold thermal discomfort responses. Then, the chosen methodological framework will be tested in a pilot study (Section 5.3). Finally the results of a larger longitudinal field study will be analysed and discussed (Section 5.4).

5.2 Review of methods to monitor people's cold thermal discomfort responses

To explore people's practices in their homes, the research focuses on the occupants and their surrounding environments, therefore information should be gathered from both. Drawing on methods from thermal comfort studies, social and psychological sciences, this section will review current methods used to survey occupants and their environments, and discuss their limitations and applicability to the research.

Many factors may influence people's practices, including the environment they live-in. Therefore prior to commencing a field study, a detailed description of the contextual information should be undertaken and available data on the local environment and built form characteristics should be identified. This initial review may include the following:

- Local characteristics and climate.
- Building characteristics.
- Indoor environmental conditions.

Much progress has been made in recent years in the tools and techniques used to monitor buildings. The forensic level of investigation will be determined by considerations such as the research question, budget, and programme. In addition to environmental parameters, the assessment of individual factors is essential and involves addressing the following aspects:

- Estimation of clothing insulation and activity level (the main individual factors for the predictive approach).
- Subjective assessment of thermal comfort using questionnaires, interviews or focus groups.
- Behaviour observation.

These approaches may be used as 'stand-alone' methods or concurrently to environmental monitoring. The information gathered may be of two types:

- Direct account from the participants, referred to as *reported information*.
- Indirect account from an observer or a sensor, referred to as *recorded information*.

The following sections will review in detail the methods used to collect both types of information.

5.2.1 Occupants survey - Reported information - Questionnaires

Questionnaires are almost always used in thermal comfort studies. As referred to in the literature review chapter, this method forms part of the current standards, listed as follows:

- EN 15251:2007, ISO 7730:2005 and ASHRAE 55:2013, for the evaluation of clothing and activity level, thermal perception and general satisfaction with the surrounding environment.
- ISO 10551:2001, for the assessment of subjective judgement on the thermal environment.

During the empirical study, the thermal comfort questionnaire may be filled-out by the respondent, a 'self-completed questionnaire', or by the researcher. The information is all recorded within the questionnaire-form, so the analysis could be systematic and require little time, particularly if computer coding is used. The questionnaire should have unambiguous instructions, and clear wording.

Research design

With regards to the format, the questions are generally closed-ended, specific, and focused on 4-types of variables, including:

- Categorical nominal: i.e. participant name, and type of clothing worn.
- Categorical ordinal: Using a scale to establish the order i.e. thermal comfort vote. A 'middle alternative' may encourage non-committal responses, but allows for gradation of opinion. For example, within a *Likert scale*, the third option will represent the 'middle alternative'. To assess thermal perception, a question with a 7-point scale answer is often used. In this case, the middle alternative will be stated as '*neutral*'.
- Quantitative discrete: Counted quantity with separated values i.e. participant's age.
- Quantitative continuous: A measured quantity with infinite values i.e. air temperature.

It is important to include alternative options, as participants may not have an answer to the question, or the topic may not be applicable to them. The questions may be ordered in a specific way, for example from general to specific points in a '*funnel shape*'.

Implementation

Questionnaires may be handed out, posted by mail or e-mail. This research uses individual-administered questionnaires: i.e. the respondent was asked to complete a structured sequence of questions in the presence of the researcher. In this case, the researcher can provide clarification if needed. The schedule include the following:

- Introductory comment.
- Completing the questionnaire.
- Closing comments.

Copies of the questionnaires used in the pilot and main study are included in Appendix A.

Analysis

To assess respondents views, opinions, and attitudes, the questions will typically include a scale, such as an attitude measurement. From the responses, the researcher can gain insight into what respondents feel or believe about a specific theme, including thermal perception and preference. A study by Brager, G. et al. (1993) reviewed the methods for assessing thermal sensation and acceptability in field studies; in particular it questioned the scales used in questionnaires. In the 7-point scale the middle rating '*neutral*' often implies that the respondent finds the environment

acceptable. However, studies have shown that the boundaries of acceptability may be stretched to ratings 3, 4, and 5. This difference in interpretation would have significant consequences in the assessment of environments.

Advantages and Limitations

Questionnaires are relatively easy to implement, as the same template is used for all participants and the data is collected in a pre-formatted condition. However, some opinions may not be captured, as the format may have omitted some parts or may not be appropriate. As with all subjective methods there might be some bias in the choice of responses made by the participant. For example participants may not want to reveal some information, or want to be perceived in a certain way. This may be the effect of social or cultural constraints.

Application to the research

In this research a questionnaire was used to collect three types of information: socio-demographic information, building characteristics and a thermal comfort assessment. Each of these were addressed using questions from established templates, including:

- English Housing Survey, which includes a household interview, physical inspection, and market value survey (National Centre for Social Research (NatCen), 2007).
- Comfort standards, which includes questions assessing the thermal environment, the participant clothing and activity levels.

These two questionnaires were completed by the researcher during the first visit to the respondents' homes. In this research the comfort questionnaire was only administered once, and not throughout the 3 to 10 days monitoring period. The main reason was that repeated surveys may have led to changes in behaviour, and may compromise the results of the observation study. It is important to note here that, as this study was primarily trying to monitor behavioural response to thermal discomfort, it differs in its aims from other studies focused on monitoring occupants thermal comfort. The assumption was that if participants assessed and reflected upon their level of comfort, they might change their behaviours. Thus the observed results may not have shown what participants ordinarily do. For example, a participant may be focused on a task and suddenly prompted to answer the comfort survey. He/she might discard the survey or stop the task to answer. Upon completion of the survey, the participant might decide to change their behaviour and act upon his/her assessed level of comfort. The monitoring study will then record a behaviour which might not have taken place if the survey had not been carried out. Moreover, repeated surveys may not only affect participants' behaviour at the time and/or directly after the survey, but also throughout the study. Participants may be more aware of their

thermal sensations as they are continuously assessed. Repeated surveys using text via mobile phone or telephone call were considered, and discarded due to this issue of potential bias in the monitoring.

Finally a third questionnaire was completed during the second visit to gain feedback from the participants on the monitoring process.

5.2.2 Occupants survey - Reported information - Focus Groups

A focus group is defined as a group-meeting where several individuals are invited to discuss a specific topic or issues under the direction of a moderator. The aim of interviewing several participants at the same time is to carry out an in depth exploration of a specific topic. During the focus group participants may discuss issues as a member of a group and respond to each others views. This method is often used in marketing to test new products and to study participants interpretations of media (Stewart, D. and Shamdasani, P., 2007). Also it has been used to gain insight from groups of experts (Gul, M., 2010). Within the context of this research, the use of a focus group was aimed at developing an understanding of why people respond the way they do, through the joint construction of meaning.

Focus groups are usually carried-out in a 3-stage process (Morgan, D. and Krueger, R., 1998) (p9):

- (Research design) Planning the focus group and developing the question(s).
- (Implementation) Moderation and collecting data.
- (Assessment) Analysing the data and reporting the results.

Research design

Prior to the meeting, the researcher should establish the following:

- Problem identification and discussion guide. Focus groups can be used to generate knowledge or hypotheses when little is known on a specific topic. The first stage of the process is to formulate a discussion guide in accordance to the research question. This tool establishes the agenda for the discussion; it will be used during the focus group as a framework to lead the discussion ensuring that all research queries are covered. It should introduce an unstructured setting, and include open-ended questions to encourage the discussion, i.e. *'How do you feel about [...]?* *What thoughts went through your head when [...]?* *What did you think about when you first saw [...]?*. The wording of the questions should be simple, and short. More structured questions may be useful when the participants are

uncertain or embarrassed about a particular topic. The order of the questions could either go from general to specific, or from most to least important. Another design approach is to quantify respondents' opinions: (1) degree of awareness, (2) influencing factors, (3) specific action(s)/attitude(s), (4) reasons for those, and (5) frequency or intensity of those (Bryman, A., 2004).

- **Sampling frame and sampling strategy.** The researcher should establish which type of participants should take part in the focus group. The invited individuals must be able and willing to provide information. The sample should also be representative of the population of interest. Generally the meeting may involve six to ten individuals recruited through convenience sampling.
- **Meeting arrangements.** These should follow a three step process: (1) introductory contacts (including: program, location, time), (2) confirmation of attendance, and (3) a reminder 24h before the focus group is due to take place. Typically the session should last between 1 to 2-hours. It should take place in a familiar and easily accessible location and the meeting room should allow privacy.
- **Recording.** It may include a combination of the following: written notes from the moderator and/or the observer, audio or video recording. If an observer joins the session, s/he should be seated away from the group and take notes on the following: what people discuss, how it is discussed, non-verbal responses, and group interaction.

Implementation

During the implementation phase, the group should be focusing on a specific theme. One way to carry-out this in depth exploration, is to refer to a common situation as a way to elicit discussions on emotion, opinions, and motivations (Bryman, A., 2004). The moderator has a leadership role and aims to provide support, direction, and encouragement. S/he should occupy a central position within the group. While guiding the session by promoting interaction and ensuring that the discussion remains on the topic of interest, the moderator involvement should be 'light', but still probe interesting or unclear participants' responses. The moderator should ensure that the meeting remains agreeable, avoiding any conflicts. The moderator should also only have a few topics to address, which may be supported by verbal questions, projective methods such as visualisation, or group involvement techniques such as role playing. In addition the moderator should manage the timing and scheduling of the session, to support this a flip chart of the agenda may be display in the room. The moderator should allow time prior to the session for setting-up equipment and arranging the room and after the session for debriefing. Within

the group some individuals might have a more prominent role than others and as a consequence steer the discussion. It is important to observe how people respond to each other's views, and build-up an opinion out of the interaction taking place. Participants may be influenced by the following (Stewart, D. and Shamdasani, P., 2007) (p19):

- Intra-personal characteristics, including participants socio-demographic, physical features, and personality. Participants may have a tendency or predisposition to behave in a certain manner across different situations, attributed to interpersonal orientation, social sensitivity, ascendant tendencies, dependability, and emotional stability.
- Inter-personal characteristics, affected by expectations about how others will act or behave, based on expectations, beliefs, or past experiences. People behave differently when they are in groups compared to when they are alone. The moderator should ensure that all members contribute to achieve the objectives of the group.
- Structural factors, i.e. the research topic and discussion guide may be conveyed in a way that the conversation may be lenient towards certain aspects.
- Temporal factors, such as time of the day and duration of the session may also affect the participants.
- Environmental factors, including the room characteristics (size, lighting, ventilation, furniture, etc.), sitting layout, and general proximity of participants.

Assessment

The researcher should review the transcript and/or other recording materials, and summarise the findings. Validity of the data collected through a focus group, may be questioned as subjective and difficult to interpret. The analysis should be aligned with the research question and objectives. This includes:

- Editing the collected data - full or partial transcript of the audio or video recording.
- Analysis of the transcript and written notes.
- Reporting on the data collection and summarising the conclusions drawn

The analysis process may be challenging. In order to reveal the ideas and themes that emerge from the discussion 3-approaches may be used:

- Collective construction of meaning: how members collaborate, achieve consensus and construct shared meanings.

- Subjective perception and motivation: how consistent is one individual in the group.
- Words and body language: including verbal expressions and sounds.

It is important to note that what may go unsaid in the discussions and what was taken for granted. The analysis may be carried out using content analysis where the unit of analysis may be (Krippendorff, K., 2004):

- Sampling unit - words or statement.
- Recording unit - descriptive (positive/negative, friendly, etc.).
- Context unit - the research focus, or marketing product.

Having defined the unit of analysis, a '*scissor-and-sort*' technique may be applied, where by the researcher reviews the transcript and identifies the relevant sections. A classification system such as colour-coding or symbols may be employed. This may be carried-out manually or using proprietary software. Content analysis focuses on making replicable and valid inferences from texts. Hypothesis emerging from focus groups may be tested in further surveys and experimental research.

Advantages

Focus groups are a qualitative research method, used to gather a rich understanding of participants experiences, beliefs and habits. This exploratory tool is used to learn about topics that are poorly understood. Using an open-question format, a large and rich amount of data is collected in a short period of time. Focus groups encourage participants to investigate the ways in which they are both similar to and different from each other. The discussions provide a context for why participants feel one way and give an in-depth view of their range of experiences and opinions. Participants are able to bring up issues in relation to the topic that are significant for them. Also it allows the researcher to interact directly with the participants and provide opportunities for follow-up questions.

Limitations

As a method to evaluate people thermal discomfort response, it has the following limitations:

- Representativeness: Group members may not be representative of a larger population.
- Group effect: Responses are not the construct of one individual but derived from the joint production of meaning. Participants may be more prone to express culturally expected views rather than individual ones (Krueger, R., 1994).

- Moderator effect: unconscious bias - 'need' to please.
- As the questions are open-ended, their analysis relies on subjective coding and interpretation.

Application to the research

In summary, a focus group creates an opportunity to listen to participants and to learn from them. The exploratory nature of the method allows the investigation of participants' behaviour and motivation. Most of the interaction consists of efforts to understand each other - '*How do others handle the same situation?*'. The results should be an account of responses to cold thermal discomfort, and the motivation that underlies these behaviours. By comparing their experiences, participants may become more explicit about their own views. However, sometimes no insight is revealed and participants are less logical and thoughtful than expected. A focus group was used in the pilot study as an exploratory tool to map variations in thermal discomfort responses and how different people may experience events differently.

5.2.3 Occupants survey - Reported information - Semi-structured interviews

Interviews may encourage the formulation of ideas by studying the interviewees own opinions, and understanding of events. One of three formats may be adopted, these include:

- Structured interview, which follows the interview guide sequencing and wording for each question.
- Semi-structured interview, which takes the discussion guide as a list of topics to be discussed, however the sequencing may vary between participants.
- Unstructured interview, which encourages the interviewer to ask new questions, use different phrasing and change the order of the questions. It is the most flexible format, which is often used in exploratory research such as oral or life history interviews (Bryman, A., 2004).

The first step in the process is the preparation of the interview guide, as a list of prompts on topics to be discussed or questions to be asked. The format of a question should be open-ended to encourage the formulation of ideas. As a rich source of information, structures or concepts may emerge from the interview transcripts. Often used as an exploratory tool, the outcome of the interview might be used to adjust the emphasis of the research.

Research design

The interview guide includes a list of topics to be covered, issues to be addressed or questions to be asked. The questions should not be too specific to avoid closing off areas of research (Kvale, S., 1996). The sequencing of the questions may start with an initial open-ended question followed by in-depth questioning or probing and ending in a summary of the session. While preparing for the interview, an appropriate setting should be chosen as accessible, quiet and private. Additionally, the recording method may include a combination of written notes from the interviewer, and audio or video recordings. Moreover interview surveys allow the researcher to follow-up interesting points and to clarify inconsistent answers. It is important to allow time after the interview for debriefing by making notes about the interviewee's body language and characteristics of the setting as well as reflecting on the meeting itself.

Assessment

To follow the interview, the output should be edited and in particular the audio-record should be transcribed. In most cases, partial transcription is carried out, where the researcher listens to the recording twice then transcribes either the entire session or the portions that are relevant. Following this, transcription and written notes may be analysed using content analysis.

Advantages

Interviews with individual subjects encourage the formulation of ideas by studying the interviewees own opinions and understanding of events. As the format is flexible, the discussions provide a context for why participants feel one way and give an in-depth view of their range of experience and opinions. Similar to the focus group, interviews allow the researcher to interact directly with respondent and provides opportunities for the clarification of responses.

Limitations

Interviews are time consuming,ethod include bias introduced by the interviewer ('interviewer-effect') and by the analysis process, which relies on subjective coding and interpretation.

Application to the research

Within this research, interviews were carried-out in the main study as an in-depth exploratory tool to investigate people's responses to cold thermal discomfort in their home. This method was used by Burris, A., Mitchell, V. and Haines, V. (2012) to gain an understanding of how and why occupants create comfort at home. The analysis of the interview transcripts allows the identification of '*comfort making themes*'. For thermal comfort these included room temperature, ventilation, clothing and taking a bath. Another study by Haines, V., Mitchell, V. and Mallaband, R. (2010) used semi-structured interviews to understand participants practices with the view to inform the design of energy efficiency measures. During the interview, a '*timeline*'

was drawn. This tool allowed participants to map when interventions and major renovations were carried out in their home. This supported the interview process in gathering a recollection of events and an assessment of the changes. In summary, semi-structure interviews create a space for participants to report on their experiences and make an account of their own responses to thermal discomfort.

5.2.4 Occupants survey - Recorded Information - Observation

The observation of participants may be carried-out directly by the researcher or via a visual device, such as video. As part of qualitative research, participants may be observed at different times of the day or week and in different contexts, alone or with friends and family, or carrying out different activities. The observer may join the participant-group, observe it, take some records, then develop an understanding of practices and behaviours. Finally, the researcher should report on the observation through a detailed written account by categorising participants and events.

The roles of the observer

The observer's role within the participants' group ranges from active to passive, and can take on the following position (Bryman, A., 2004):

- Complete participant. The researcher is a member of the social setting, this may create over-identification issues from the observer.
- Participant and observer. Semi-involved in situation, the researcher may take the role of an interviewer. Again this may lead to over-identification or misunderstanding.
- Complete observer. No interaction with participant(s), the researcher carries out an unobtrusive observation. This may lead to some misunderstanding.

It is important to ensure that the relationship between a researcher and participant(s) are not simply a one-way process of extracting information but to also provides something in return for the participants.

Structured observation

Prior to the start of the data collection, the aim and objectives of the study should be defined as well as the observation categories, including: who and/or what and/or when to observe. The researcher aims to record systematically using a schedule of observation categories. Each participant is observed for a predetermined period of time using the rules set in the observation schedule. This systematic record allow the aggregation of the participants' behaviour. The

observation categories may be inclusive or exclusive, and the analysis process will require a certain amount of interpretation.

Observation schedule

To establish an observation schedule, the types of behaviour to be observed should be specified, as well as the unit of observation, for example: participant name, location, time, duration, rating (low to high), comments, etc. The categories of behaviour listed should be mutually exclusive, clearly defined, and focus only on a few aspects, such that the recording system is easy to operate. The observer will be recording whatever is happening in real time or after the event depending on the role chosen. It may require a certain amount of interpretation.

Advantages and limitations

As an inductive research method, observations should conclude once theoretical saturation is reached (Bryman, A., 2004). This stage arises when successive periods of data collection have identified a category and confirmed its role. This is also a limitation of this method, as there is no clear justification of knowing when to stop. Another limitation of the method may be the setting of categories, as the observer might not be able to identify the intention(s) of a behaviour. Additionally a number of biases may occur. During data collection, participants' behaviour may be influenced by the observer, whilst within the analysis the coding may raise ambiguity. On the other hand this method facilitates theory building as no specific hypothesis is tested. In some cases follow-up studies may be required, using focus groups or interviews.

Application to the research

Observation is often used in thermal comfort studies to estimate people's clothing and activity levels. For example, the study by Morgan, C. and de Dear, R. (2003) used observation to investigate clothing behaviour in a shopping mall. Every fourth person passing in front of the observer had their clothing insulation rated. These observations were made every day for a 6-month period, from which daily mean clothing level was calculated. The results showed a strong relationship between outdoor temperature and clothing level. Using observations was one of the methods first selected to be implemented in this research as it can map actual responses to thermal discomfort. However, the bias introduced by the observer's attendance in the home was too great to be applied in either the pilot or the main study.

5.2.5 Occupants survey - Recorded Information - Diaries

Diaries are often used to explore different kinds of behaviour in participant's natural setting. Although self-completed, the method is similar to structured observation. Diaries may take one of the following formats:

- Self-completed interviews are recording in prose the amount of time spent on different kinds of activity. This method allows to capture participants' own accounts of the type of perceived behaviours and practices, and the time spent on those. Self-completed interviews may be considered "*unreliable*" (?), as the participants may only complete the diary at the end of a day and forget events, or may not realised that events had occur as these may be embedded in their practices (Bolger, N., Davis, A. and Rafaeli, E., 2003).
- Self-completed questionnaires involve filling-in a form with a precise set of questions, often close-ended, at a precise time interval. The questionnaire diary is often a short survey, and may be event-based or time-based designs with fixed-time schedules or variable schedules (Bolger, N., Davis, A. and Rafaeli, E., 2003) (Clear, A. et al., 2013). This method requires participants to be committed to complete the series of repeated surveys. Moreover the action of completing the diary itself may impact directly on the activity, as the participant may have to stop the activity to fill-in the survey (Reis H. and Gable, S., 2000).
- Automated diary, wearable logger or audio recording equipment can be worn by the participant and produce a signal at a pre-defined time interval to prompt an entry. This method is often used in behavioural medicine (Bolger, N., Davis, A. and Rafaeli, E., 2003) (Smyth, J. and Stone, A., 2003). The advantages of such method is to randomised the signal, and to provide precise time-stamp for responses, which can then be linked to other data sources. Similarly a portable camera may record pictures when triggered by changes in movement, temperature, light intensity, etc (Sellen, A. et al., 2007). The main limitations of this method are the cost of the device, storage capacity, connectivity, battery life, maintenance, but also the fact that the participants may forget to wear the logger.

In summary, the participants may be active or passive. The output will be time-stamped, and therefore duration and frequency of particular behaviour can be estimated. The analysis will then be able to report on the frequency and probability of specific behaviours. This method is widely used for time of use surveys studying lifestyle patterns and well-being (Gershuny, J., 2011).

Automated diary in cognitive psychology and physiology

In the field of cognitive psychology, automatic diary methods have been used as external memory aids for patients with neurodegenerative disease and brain injuries (Berry, E. et al., 2007). Using a wearable device, episodic memories grounded on personal experiences are recalled. This form of memory is the basis for semantic memories, such as fact and concept, which guide actions. Wearable sensors record images and associated experiences from the participants point of view. The automated nature of the data collection records events without a conscious thought. As sensing technologies have developed over the past few years, many significant advances have taken place in the area of people's activity assessment (Trost, S., McIver, K. and Pate, R., 2005). One of the most noticeable has been the rapid uptake of accelerometry, which measures movement as a bio-mechanical effect (Patterson, S. et al., 1993). This objective technique enables the estimation of activity levels in a free-living environment, for periods of time representative of a person's daily activity level. Supported by other methods such as heart-rate monitoring and automatic visual diaries, this mixed-method approach collects objective measurements of daily activity levels as reviewed in Chapter 4.

Instruments

In this research, the SenseCam is used as a data-logger and a visual diary. This instrument's main advantages are to be accredited for general use, relatively affordable, hold a large storage capacity and optimised power consumption. In the field of cognitive psychology, this tool has been used as an external memory aid (Hodges, S. et al., 2006). The device is worn around the neck and placed on the chest. Of similar size to a badge, the SenseCam takes photographs when triggered manually and/or automatically, by a timer or by changes in sensor readings. The sensors include temperature, light level, PIR, accelerometer and magnetometer. The SenseCam provides two types of outputs: (1) a record of measurements taken by each sensor and (2) a visual diary of the participants activity in their home. SenseCam's automatic visual diary is used to validate the estimations and inferences made by other data collection methods, in particular clothing and activity levels, and participants location in the home. To monitor people's behaviours and practices, other methods may be considered including stationery cameras. These devices may be linked to a server where the information is stored in the home or on the Cloud. There are drawbacks to this method. First the equipment may be more expensive and intrusive than the wearable option, as cameras may installed in every rooms in the home. The number and position of cameras should be contingent on the behaviour to be monitored. Also the data analysis process may require image recognition processing, which can be computationally very challenging (Suarez, J. and Murphy, R., 2012). Finally, additional wearable sensors will need

to be used by the participants to monitor motion.

Advantages and limitations

Diary methods may be convenient for the respondent, as they can be conducted in their own time and at their own speed. This may uncover sequences, details or behaviours that may otherwise have been overlooked. The data collected in diaries is in large the responsibility of the participant. This itself may lead to 'respondent fatigue', changes in the participant behaviour, and for self-reported diaries misreporting (Gershuny, J., 2011). Moreover, data may be misinterpreted in the analysis as the researcher can not ask for clarification. Therefore diaries may be used in conjunction with other methods such as follow-up interviews.

Application to the research

Automated visual diaries were used in the pilot and main study, capturing occupant's interactions with their home and their responses to thermal discomfort. This objective and qualitative technique enabled the capture of a person's daily practices, with minimal impact and discomfort. Analysis of the visual diary uses first manual and then automated segmentation techniques to identify events, described in the following sections. In the main study, the analysis was automated therefore little bias was introduced, only in the choice of filtering algorithm and the subjective interpretation of the reason(s) for an event to occur. Beyond its use as a stand-alone method, the automated visual diary was used in this research to validate outputs from other devices. As review in Chapter 4, the recorded images were compared with temperature, acceleration and the heart-rate readings.

5.2.6 Occupants survey - Recorded Information - Wearable sensors

Specific physical properties may be monitored using wearable devices with hardware-based sensors, such as acceleration, heart rate or temperature (See Table 5.1). The recording of these sensors may be used to monitor changes in locations and activities.

Sensors data processing

Recording data includes the concurrent use of sensors to capture information and dataloggers to store this information. Once the information has been recorded, it may be downloaded manually with proprietary software, or automatically with the use of a transmitter, receiver and proprietary software. Various methods can be used for data recording and data processing.

To process the downloaded information, existing platforms may be employed, such as R (<http://cran.r-project.org>); which can be used as the main computational tool, but also can be used as an add-on to an existing set of statistical tools. In the case of the automated diaries, R may be used to synchronise time series data, carrying out descriptive and inferential statistics, implementing queries to dataset, processing signal output, and running algorithm.

Table 5.1: Overview of the most frequent sensors used in wearable devices

Sensor	Sensor	Ware	Data Output	Units of measure	Common Use
Motion	Accelerometer	Hardware	Measures the acceleration that is applied to the device on two or three physical axes, including the force of gravity	m/s ²	Monitoring motion, or acceleration along a single axis
	Gyroscope	Hardware	Measures the rate of rotation applied to the device around each of the three physical axes	rad/s	Monitoring rotation
Position	Magnetometer	Hardware	Measures the ambient geomagnetic field around the device for the three physical axes	μT	Determining compass coordinate
Physiological	Heart-rate monitor	Hardware	Measures the number of beat per minute of a person's heart	Bpm	Determining activity intensity, and type
Environmental	Thermometer	Hardware	Air temperature	°C	Monitoring air temperatures
	Barometer	Hardware	Relative humidity	%	Monitoring dewpoint, absolute, and relative humidity
	Photometer	Hardware	Illuminance	Lx	Monitoring 'brightness', which could be related to the change of location
	Passive infrared sensor (PIR)	Hardware	Determine the presence of infrared light radiating from objects in its field of view. i.e. a person, a warm drink, or a radiator	Binary [0,1]	Monitoring motion, and activity

The most important feature for the analysis is the capacity to slice and/or to extract data from large datasets. In particular, when validating an event or activity, the following steps may be executed:

- Extracting a subset of data - for example, looking for passive infrared sensor (PIR) output only.

- Find a particular variable - for example, call for the corresponding set of photo, when [PIR=1] per minute <20-counts.

In addition, the analysis might execute query commands to retrieve data from database management systems, such as PostgreSQL (Li, Y., and Baron, J., 2012).

For data recording and processing, proprietary software may be used. For example, the study by Spataru, C. and Gillott, M. (2011) has developed a soft-computing application written using Visual Basic to correlate various information, such as occupancy information and electricity consumption to detect the occupants activities. Soft-computing applications are important to correlate different databases and provide the necessary statistics. All data records should have an associated error code and validity check such that any non-valid data can be identified and assessed. Moreover, pre-designed automated standard graphs will help to analyse data efficiently and spot problems in monitoring from an early stage.

Application to the research

The choice of wearable sensors is an integral part of the automated diary method. These are used to collect information on the participants and the surrounding environment. Sensors may also be used to trigger a camera to take a picture, or to prompt the participant to record an entry in a self-completed diary. As summarised in Table 5.1, outputs from wearable sensors may provide spot-measurement or longitudinal information on the participant's motion, position/location, physiological state, clothing level, etc. The analysis of outputs from wearable sensors may be automated using open-source or proprietary software, such that little bias is introduced. As reviewed in Chapter 4, SenseCam and Kalenji heart rate monitor were used in this research. Motion was recorded using the SenseCam's tri-axis accelerometer (Kionix KXP84), temperature at the surface of clothing was recorded using the SenseCam's temperature sensor (Nat Semi LM75), and heart rate was recorded using the Kalenji monitor. Finally, the output of the SenseCam's light intensity sensor (TAOS TCS230) and a passive infrared detector (Seiko SKP-MS401) were used to identify some responses to thermal discomfort, such as "*having a warm drink or warm food*" or "*putting on an item of clothing*" (as reviewed in Section 4.3.3). Although wearable sensors enable multiple objective quantitative information to be measured, the main limitations are as follows (Patel, S. et al., 2012):

- Devices may be positioned incorrectly; this may lead to missing data or extreme value(s).
- Participants may forget to wear the device.
- Potential Hawthorne effect, participants may change their behaviours as they know they are being monitored.

The first limitation may be addressed by using complementary devices, for example accelerometer and heart-rate to monitor motion. In this research, the second and third limitations were in part addressed by an interview taking place at the end of the monitoring study. Participants are asked if they *forgot to wear the devices*, and if they *forgot that they were wearing the devices*. The results are reviewed in the following Sections.

5.2.7 Occupants survey - Recorded Information - Indoor location monitoring

Interest in indoor localisation has rapidly expanded with the development of a variety of sensors for tracking people and activity recognition. Sensors assessing people's motion and activity level may also be used to provide information about their location. Then a record may be established over which rooms are occupied and what activities may be being carried-out. In ubiquitous computing two types of sensors are used, wearable and static sensors (Liu, H. et al., 2007). Static sensing methods include the following (Spataru, C. and Gauthier, S., 2014):

- Wireless networks (Xiong, J. and Jamieson, K., 2013).
- Acoustic sensors which detect sound produced by people.
- Air pressure sensors which detect changes in air pressure resulting from opening doors and windows.
- Passive infrared sensors which are sensitive to heat waves emanated from warm or cold objects. However, there are issues with this method. For example, when more than one person is in the same space, the PIR readings do not show greater peaks and do not differentiate between the presence of different occupants.
- Carbon-dioxide sensors which detect changes in CO₂ concentration associated with people's activity in the home, but also on other factors, such ventilation rate. This may lead to inaccurate or misinterpretation in the results.

Wearable sensors may be used concurrently to these static sensors, or as a stand-alone method. Indoor localisation may be determined through motion and direction, as the outputs of an accelerometer and magnetometer or radio frequency identification (RFID) (Spataru, C. and Gauthier, S., 2014). The SenseCam includes built-in sensors such as accelerometer, magnetometer, PIR and temperature sensors that monitor motion, position, and environmental variables. In particular, positional sensors measure the physical position of the device worn by the participant. To this effect the SenseCam's magnetometers measures the components of earth's geomagnetic

field along three axes. To determine the location of a participant, the SenseCam's magnetometer and accelerometer output may be analysed together in an indoor-mapping analysis process (Zhu, R. and Zhou, Z., 2004) (Xuan, Y., Sengupta, R. and Fallah, Y., 2010). The main sources of measurement errors of a magnetometer are the offsets of the frequency and magnetic 'contamination' by ferrous materials on and around the participant or the device. Also if the sensor is rotated as the measurement is made, an additional error is generated (Shala, U. and Rodriguez, A., 2011).

Application to the research

Having reviewed emerging tools in location sensing technologies (Spataru, C. and Gauthier, S., 2014), the study considered using RFID systems. The active RFID tag could have been worn by the participant in conjunction with the SenseCam, but a large number of RFID readers would have been needed to monitor each room within the dwellings (Li, N. and Becerik-Gerber, B., 2011). This system was beyond the financial scope of this project. Moreover these readers would ideally have been mounted to the walls of the participants' home. These dwellings were not test-houses but peoples' homes, therefore the research opted for inertial navigation system using accelerometer and magnetometer as the indoor location sensing solution. Initial analysis of the monitoring study showed that participants' location needed to be re-assigned every 15-minutes using images from the visual diary. This was due to the fact that each new position is determined by the past position, and therefore each measurement is prone to cumulative error within the previous measurements. Unfortunately due to time and resources constraints, the participants' locations were only ascertain for the pilot study, and not for the main study. Future research may employ systems similar to the one used in mobile phone as the combination of accelerometer, magnetometer, gyroscope and altimeter. This system will increase the accuracy and processing time (Shala, U. and Rodriguez, A., 2011).

5.2.8 Building survey - Local characteristics and climate

One of the first stages of the field study is to map local characteristics that could impact on people's indoor thermal comfort in winter. The adaptive approach may be used in the analysis, which aims to compare monitored indoor operative temperature against outdoor conditions. Previous field studies report that preferred indoor operative temperature is associated with outdoor temperature, and that their relationship is linear (Humphreys, M., 1978). It should be noted however, that in the context of cold thermal discomfort during the English Winter heating season, where running mean outdoor air dry-bulb temperatures are routinely below 15C, that the adaptive approach is not deemed applicable in such temperatures (CIBSE:TM41, 2006). In this

study, external dry-bulb temperature was monitored. Data was retrieved from dedicated external sensors deployed for the pilot study, as HOB0-U12-012; while for the main study data retrieved from local weather stations using Weather Underground (<http://www.wunderground.com/>). Additionally, it was important to gain insight into the neighbourhood built-form and density.

5.2.9 Building survey - Building characteristics

To assessing the conditions of the case-study buildings a standard assessment framework may be used, for example:

- As a stand-alone module - the Integrated Household Survey (ONS) and the English Housing Survey (EHS) which includes household interviews, physical inspection, and market value surveys (National Centre for Social Research (NatCen), 2007).
- As part of a module - the Energy Performance of Buildings Regulations 2012 and the Energy Performance Certificates provide a standard assessment procedure for existing dwellings, the RdSAP. It includes sections on the building location, layout, fabric and systems (BRE, 2012).

Using these two frameworks, the research should include the following steps to gather information on the building characteristics:

- Review of the case-study neighbourhood morphology, built-form, detachment, age-band, and conservation type. A 'desk' study may collect information from area-maps to determine the orientation and built-form. Additional details may be gathered from the conservation area register, the smoke control zone register, planning and building regulations, and the land registry.
- Assessment of the case-study layout. During a site-visit the following should be ascertained to complete a dimension survey (floor area, room height, and loss perimeter): the number of floors (including extensions and 'rooms-in-roof'), the number of habitable rooms, the number of windows and doors
- Assessment of the building fabric, including: main wall construction, window type and area, number of draught proofed windows and doors, floor and roof construction.
- Assessment of the building systems as lighting, space heating/cooling, water heating and ventilation. Details include: percentage of low energy lights, number of heated habitable rooms, heating system and associated controls, and renewable (PV, wind turbine, and solar heating).

During the site visit, this data may be recorded using standard forms, notes, sketches and a measurements log. The visit should include an inspection of the interior and the exterior of the dwelling. Using an existing assessment framework allows for reliable data collection procedures, that can be put in the context of other cases-studies. Also feedback may be given to the participants in a standard format.

5.2.10 Building survey - Internal environmental conditions

5.2.10.1 Ambient air temperature, (T_a)

The ambient air temperature is defined as the temperature of the air around the participant and is expressed in kelvins (K) or degrees Celsius ($^{\circ}\text{C}$). The characteristics of the instrument should be as follow (ISO 7726:2001):

- Measuring range: 10 to 40 $^{\circ}\text{C}$.
- Measuring accuracy: required ± 0.5 $^{\circ}\text{C}$; desirable ± 0.2 $^{\circ}\text{C}$.
- 90% Response time: the shortest possible.

To comply with this set of standard requirements, this research project used Onset HOBO U12-012 data-loggers for thermal monitoring. The loggers recorded ambient air temperature with an accuracy of ± 0.35 $^{\circ}\text{C}$ at 5-minutes intervals. The whole set of loggers were first calibrated by being exposed to constant thermal environmental conditions set at 20 $^{\circ}\text{C}$ and 50% RH for 12-hours in thermal chamber at the Bartlett School of Graduate Studies, UCL. Results from the calibration test showed that all loggers had accuracies within the range specified by the manufacturer.

Three set of 4-dataloggers were fastened to wooden-poles, and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground, to comply with the requirements set by ISO 7726:2001, as it was hypothesised that the home environment might be heterogeneous. For the purpose of the analysis, the sitting and standing positions were considered; the standing position was chosen as more representative of horizontal thermal stratification, calculated as the mean temperature over three heights: 0.1m; 0.6m; and 1.7m. These wooden-poles were then used in the main study. While monitoring, the sensors were located in different rooms, close to participants typical activity and away from sources of direct light and heat.

5.2.10.2 Mean radiant temperature, (T_r)

The mean radiant temperature is defined by ISO 7726:2001 as '*the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure*', and is expressed in kelvins (K) or degrees Celsius (°C). There are different ways of estimating indoor mean radiant temperature, these include: (1) either by applying equations derived from empirical relationship with dry-bulb temperature and mean air velocity, or (2) by measuring surface temperature and view factor, or (3) by measuring it directly with instruments such as a black-globe thermometer.

The characteristics of the measuring instrument should be as follow (ISO 7726:2001):

- Measuring range: 10 to 40 °C.
- Measuring accuracy: required ± 2 °C; desirable ± 0.2 °C.
- 90% Response time: the shortest possible.

As the field studies were carried out in winter, it was assumed that there will be little window operation, and therefore a minimum air velocity of 0.1 m/s was adopted (Hong, S. et al., 2009). With air velocity below 0.15 m/s, it is assumed that (T_a) = (T_r) (ISO 7726:2001, table 3).

5.2.10.3 Relative humidity, (RH)

The relative humidity is defined as the ratio between partial water vapour pressure and saturated water vapour pressure at a prescribed temperature and is expressed in percentage (%). There are different ways to estimate relative humidity, either by applying equations derived from empirical correlations to calculate it, or by measuring it using instruments such as a psychrometer. The characteristics of the instrument measuring partial water vapour pressure should be as follow (ISO 7726:2001):

- Measuring range: 0.5 to 3 kPa.
- Measuring accuracy: ± 0.15 kPa.
- 90% Response time: the shortest possible.

Note: from ISO 7730:2005 Annex D:

$$RH = \frac{10 \times P_a}{e^{(16.6536 - \frac{4030.183}{T_a + 235})}} \quad (5.1)$$

where RH is the relative humidity in %, P_a is the partial water vapour pressure in Pa, and T_a is the dry-bulb temperature in °C.

Onset HOBO U12-012 data-loggers were used for thermal monitoring in this study, capturing relative humidity levels with an accuracy of $\pm 2.5\%$ at 5-minutes intervals. Again, results from the climate chamber calibration test showed that all loggers had an accuracy within the range specified by the manufacturer.

5.2.10.4 Air velocity, (V_a)

Air velocity is defined by its magnitude and direction and is expressed in metres per second (m/s). Mean air velocity is defined by the average of the velocity over an interval of time and by the standard derivation of the velocity. Air velocity may be measured using an anemometer, either multi or non-directional. The characteristics of the instrument should be as follow (ISO 7726:2001):

- Measuring range: 0.05 to 1 m/s.
- Measuring accuracy: required $\pm(0.05 + 0.05v_a)$ m/s; desirable $\pm(0.02 + 0.07v_a)$ m/s.
- 90% Response time: required 0.5 m/s; desirable 0.2 m/s.

In this research, air velocity was measured in the main studies first visit using a hot-wire anemometer (directional appliance). The Testo 425 was used to capture air flow speeds with a range of 0 to 20 m/s and an accuracy of $\pm(0.03 + 0.05v_a)$ m/s. Results from these field tests showed that air velocity was below 0.1 m/s in all cases. This concurred with the assumption that minimum air velocity will be set at 0.1 m/s during winter as little window operation occurred (Hong, S. et al., 2009).

5.2.11 Summary

This research proposes to use a set of methods, with the intention of creating links between the different approaches and their output. It uses approaches in which the residents and the dwellings thermal comfort system are in a reciprocal dynamic and interactive relation, Vischer, J. (2008). The research considers the resident as an active agent who interacts with the dwelling's thermal comfort system. It also looks at the extent of this interaction, associated influencing factors, system boundaries and thresholds.

Drawing upon thermal comfort literature, some general issues are found with regards to the following:

- Practical constraints of data gathering, including sample size and characteristics.
- Mixed method approach may give different weight to variables; for example reported versus predicted mean thermal sensations.

- Studies often use cross-sectional surveys to report on thermal comfort which is part of a dynamic process as informed by past experiences.
- Non-thermal factors being omitted from the assessment including psychological, social, and contextual elements.
- Non-uniformity of physical measurements.

Moreover mapping of behaviour and practices should be mindful of the limitation of the methods used and of the incomplete nature of the elicitation process. Reported information in focus groups, interviews and questionnaires are reliant on participant recollections of an event and may be inaccurate. To complement these methods objective data-collection using wearable sensors and automated visual diary are carried out.

To answer some of these issues, this methodological framework consists of a combination of existing methods used to assess thermal comfort, and methods drawn from social and psychological sciences. Following this chapter's review, six methods were selected, including:

- Two related to the environment - building survey and environmental monitoring.
- Four associated with occupants survey - questionnaires, semi-structured interviews, focus groups, and automated visual diaries.

This combination of methods was assessed in a pilot study and will be discussed in more detail in the following sections.

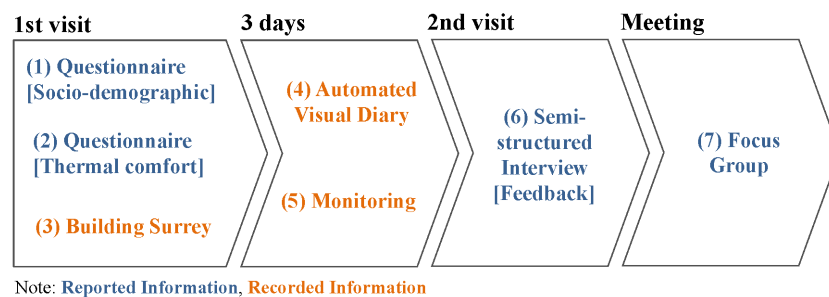
5.3 Pilot study - results and analysis

Following the review of methods used to gather people's responses to thermal discomfort, a pilot study was carried out to assess the proposed methodological framework. In particular it allowed a review of the validity and limitations of current standard methods and new methods using ubiquitous sensors. This pilot study was undertaken in the winter of 2010; prior to the study described in Chapter 4. This section will first introduce the pilot study research design, then describe its results and finally discuss the findings.

5.3.1 Study design

The study was carried out in London, UK, over the winter of 2010. Using convenience sampling, 11-participants living in 10-different dwellings were monitored over a minimum period of three consecutive days, two weekdays and one weekend day. This six weeks field study was followed by a focus group, which was attended by 9 of the 11-participants. This focus group aimed to gain insights from respondents on their typical responses to thermal discomfort. The data collection sequencing is summarised in Figure 5.1.

Figure 5.1: Pilot study data collection sequencing.



5.3.1.1 Sampling frame and sampling strategy

As introduced in the research design chapter, the pilot study sample frame was based on socio-demographic and building characteristics, in particular:

- Participant's gender, age and weight.
- Participant's occupation, and their tenure status.
- Property's age band, position, built form, energy efficiency rating and heating and ventilation system.

The sample attributes are summarised in Figure 5.2, Figure 5.3, Figure 5.4, and Figure 5.5. Participants were selected purposely to gain insights into each sample frame variables; for example:

Does cold thermal discomfort responses differ with age? To answer this question participants from different age-groups were selected.

Having defined the essential qualities of the sample, a call for participants was sent out to friends and family members who may have some of these characteristics. Twenty people were contacted of which eleven living in ten different dwellings agreed to take part. The sample consisted of four males and seven females, most participants were aged between 25 and 34 years old, and the sample weight varied from approximately 50 to 80 kg. Located in London, the dwellings were built in different periods, dated from 1850 to 2006. Some incorporated features such as retrofitted central, communal or district heating systems. All dwelling were naturally ventilated, and their energy efficiency ratings varied between B and E. These ratings were calculated using RdSAP worksheet version 9.83 (BRE, 2012).

Figure 5.2: Pilot study sample frame - Physiological characteristics (ISO 8996:2004 Annex C).

Age (years)	Weight (kg)				
	50 kg	60 kg	70 kg	80 kg	90 kg
Women					
20		P03			
30	P01	P06, P07, P08, P11			
40		P05	P04		
50					
60					
Men					
20					
30			P09	P02	
40					P10
50					
60					

Figure 5.3: Pilot study sample frame - Physiological characteristics distributions.

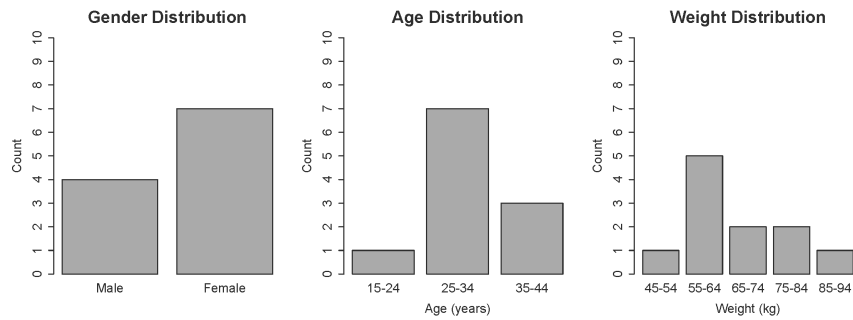


Figure 5.4: Pilot study sample frame - Personal characteristics distributions.

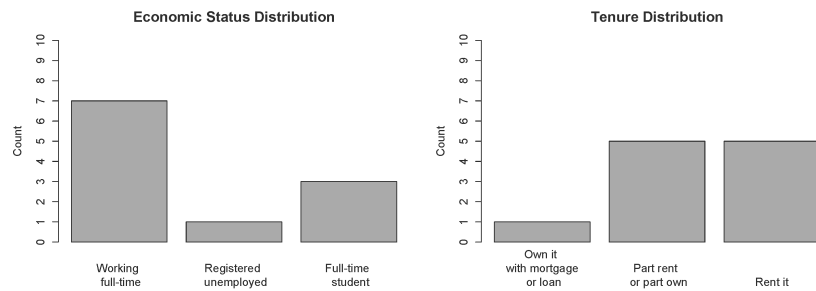
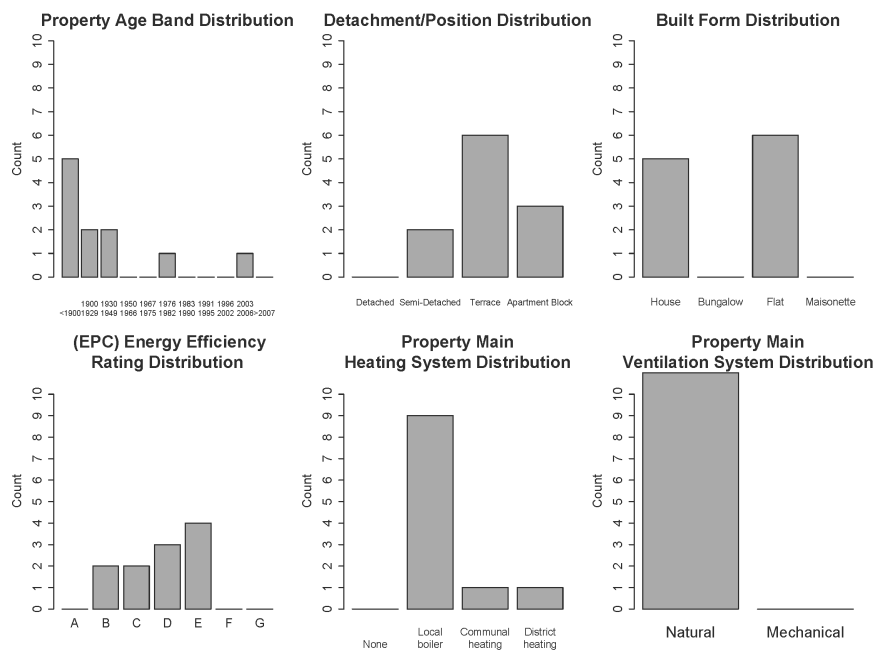
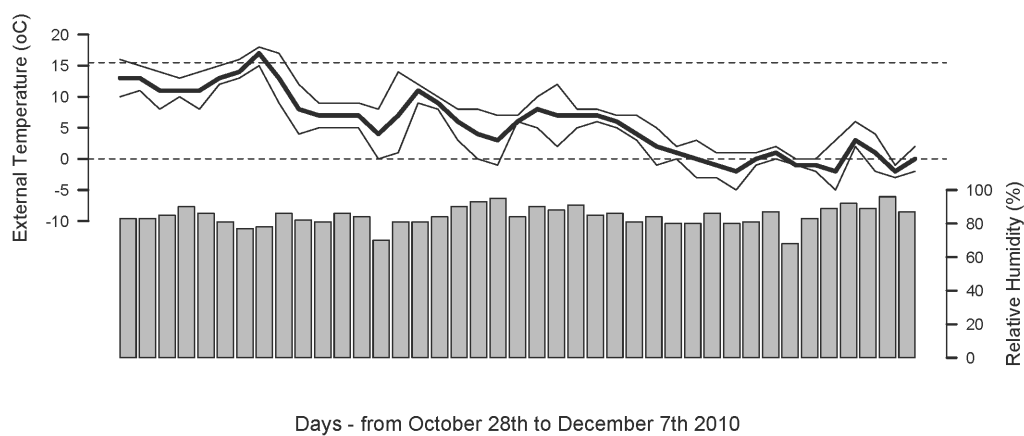


Figure 5.5: Pilot study sample frame - Building characteristics distributions.



The pilot study was carried out from the 28th of October to the 7th of December 2010. This period was selected as the monitored external temperatures were expected to be below the degree-day threshold of 15.5°C, and low enough to require space heating. After analysis as shown in Figure 5.6, it was confirmed that during these six-weeks, the external temperatures were below 15.5°C for 95% of the time, therefore the study was carried out in the heating season, and winter benchmarks and indices may be applied (Chartered Institution of Building Services Engineers (CIBSE), 2006). The external mean temperature was 5.7 ± 5.2 °C, and the external mean relative humidity was 85 ± 6 %. During this monitoring period the warmest day was on the 4th of November, and the coldest day was on the 28th of November.

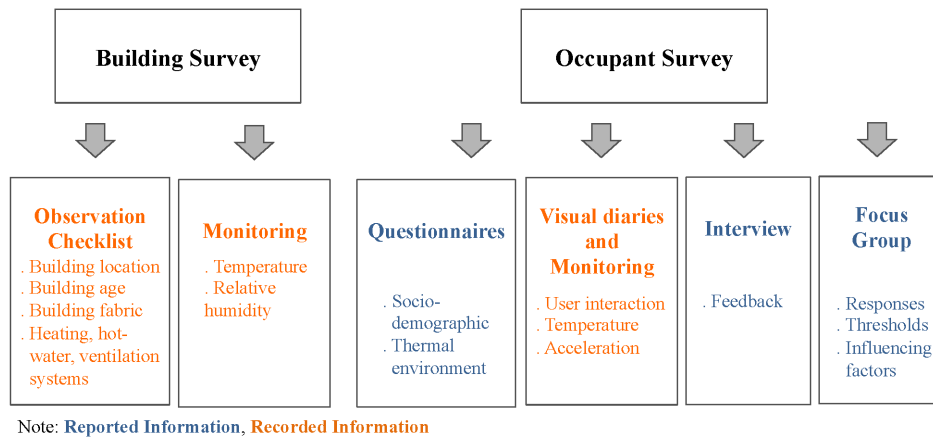
Figure 5.6: Mean external relative humidity, and external temperature profile as minimum, mean and maximum values for each monitoring days. The degree day threshold of 15.5°C is identified by a dotted line.



5.3.1.2 Mixed methods framework

Following the literature review, six data-collection methods were selected. In making these choices, there are questions raised about the validity of mixed methods to gather information, however these are often the norm in thermal comfort field studies as described in ISO 7730:2005 and ASHRAE 55:2013. This approach enabled the collection of a wide range of information, which can be compared to current benchmarks and other studies. The methodological framework used for the pilot study is illustrated in Figure 5.7.

Figure 5.7: Pilot study methodological framework.



Questionnaires

Two questionnaires were completed with the householders during the first visit using recognised templates (see Appendix A), details of which follow:

- **Questionnaire A.** The intention of this questionnaire was to investigate participants' assessments of their thermal environments. The respondents were asked to rate their thermal perception, affective assessment, thermal preference, acceptability, and tolerance; using ISO 10551:2001, Annex B set of questions. The questionnaire also used a combination of standard questions taken from ASHRAE 55:2013 (Appendix K), and RP-884 database (de Dear, R., Brager, G. and Cooper, D., 1997). Thermal perception was rated on a 7-points scale. Metabolic rate and thermal insulation level were estimated, using ISO 7730:2005 Annex B and C respectively. This account of reported thermal assessment was later compared to recorded information.
- **Questionnaire B.** Respondents were also asked to complete a second questionnaire focused on socio-demographic variables. It included household characteristics, housing history, general health and economic activity status, using the questions taken from the Survey of English Housing (National Centre for Social Research (NatCen), 2007). These reported characteristics were later used to categorise the results of the pilot study.

Building survey

A building survey was completed during the first visit. The visual inspection of the dwellings was conducted both internally and externally, using RdSAP worksheet version 9.83 (BRE, 2012). Information collected included details on built form, age band, property layout, fabric type, heating, ventilation and hot-water systems. The outputs were later used to calculate the energy efficiency rating of each property, and to categorise the results of the pilot study.

Monitoring

The monitoring took place throughout three days. Onset HOBO U12-012 dataloggers were used to record air temperature, relative humidity and illuminance. These compact devices were programmed to start 30-minutes before the questionnaire started, and recorded a reading every 5-minutes. Each datalogger was labelled with a unique code, and their position in the dwelling recorded. Their locations in each dwelling were defined by the layout and occupants' living patterns. Typically, dataloggers were placed in living rooms and bedrooms, these rooms were defined as zones. The effective internal temperature was weighted as a combination of average temperature from each zone in the dwelling. The dataloggers were placed away from potential heat sources and located at waist height. Over the same period external conditions were monitored, using similar dataloggers recording dry-bulb temperature, relative humidity and illuminance levels. The dataloggers were positioned inside and outside dwelling after carrying out the building survey. The researcher and the participant did a walk-through, and agreed the most suitable location. At the end of 3-days, the researcher collected the devices with the participant, and asked if there was no disruption during the monitoring, i.e. '*Did a logger felt down?*', or '*was it moved?*'. The results of this monitoring were used to assess the dwelling hygrothermal conditions, and to model predictive indices for each participant throughout the 3-days.

Visual diary

A SenseCam was handed out to each participant during the course of the first visit, this usually took place just after the questionnaires. The researcher showed the participant how to turn on/off the device, how to recharge the device, the privacy settings (see Chapter 3), and how to reset the device. Sometime the SenseCam could not be switched-on for technical reasons; some participants had to reset the device manually by pressing the SenseCam's 3-buttons at the same time for 10-seconds. None of the data recorded prior to the reset was lost, only the internal clock was readjusted to "00:00:00 01/01/2000". Then the participant was asked to take a picture of a clock, so the data could be synchronised at later stage. To follow this introduction, the research discussed how the equipment should be used during the 3-days monitoring period.

As the SenseCam was to be worn only when the participant was at home, a typical day was reviewed step-by-step, described as follows:

- In the morning, the SenseCam should be first worn after dressing-up for the day.
- If the participant was to go-out, the SenseCam should be taken off just before leaving the home, and placed near the entrance door or on the coat-stand.
- When returning home, the SenseCam should be worn again. As the monitoring took place in the winter, the advice was "*coat on - SenseCam off*", and "*coat off - SenseCam on*". If the participant forgot to wear the SenseCam, then he/she noted down the occurrence, the record was handed to the research during the second visit.
- In the evening, the SenseCam should be taken-off when going to bed.

At the end of the introduction, a "*how-to*" leaflet was handed out, which summarised the process. During the second visit and at the end of the monitoring, the participants handed-back the SenseCam, and a short feedback interview was carried out, described below. As the pilot study lasted only 3-days, none of the participant had to recharge the SenseCam. Concurrent to the monitoring, visual diaries were collected through the three consecutive days. The recordings included a series of photographs, and output from the temperature sensor, light intensity and colour sensor, passive infrared detector, tri-axis accelerometer, and magnetometer. Around 3,200 images were generated for each participant. These outputs enable participant whereabouts to be mapped and in particular their locations, and activity and clothing levels.

Semi-structured interview

During the second visit, a short feedback semi-structured interview was carried out, which aimed to gather information on the practicalities of the methods employed, in particular the automated visual diary (see the Discussion Guide in Appendix A). The main questions were '*At times, did you forget you were wearing your SenseCam?*', and '*Did the SenseCam change the way other occupants acted?*'. The two questions aimed to understand if the participant and other occupant(s) became more/less self-conscious of the sensors, changed their behaviour, and therefore introduced bias. Results of this interview are reviewed in the following Section.

Focus group

At the end of the pilot study 9-participants took part in a focus group. This session facilitated the gathering of reported information on thermal discomfort response (see Appendix A). Using a focussing exercise, participants were first asked to write down their thoughts for a given scenario illustrated by a picture. Then open-ended questions addressing typical responses to

thermal discomfort, associated thresholds and influencing factors allowed to gain insight of the participants' relationship with their home thermal comfort system. During the session an observer recorded participants' non-verbal communication, body language and mood. Together with the transcript of the discussion, information was coded using qualitative data analysis software, Nvivo. This content analysis allowed to gain an understanding of the participants' responses to thermal discomfort and associated influencing factors.

5.3.2 Results

The analysis consists of the review of the households characteristics, and reported, observed and predicted thermal perception and responses to thermal discomfort. The data collection methods informed each for these three categories, and are divided as follows:

- Reported information was derived from participants' direct accounts in questionnaires, interviews and focus group.
- Observed information was gathered using a combination of qualitative information from the visual diary, and quantitative information from the environmental monitoring and the wearable sensors.
- Predicted information was derived from the current standards and guidelines, including the predictive indices and CIBSE environmental design criteria.

The analysis of the data collected is structured in three parts:

- Reported and predicted information. During the first visit participants were asked to assess their thermal environment, in particular to evaluate their thermal perception and preference. These subjective judgements were then compared to the calculated predictive mean vote.
- Reported and observed information. Results of the focus group were used to draw a list of responses to thermal discomfort and associated keywords. In parallel the SenseCam outputs were analysed to identify actual responses to thermal discomfort.
- Observed and predicted information. This analysis was three-fold:
 - Monitored indoor temperature and humidity were compared to CIBSE environmental design criteria (2007).

- Monitored environmental and personal variables were used as input to the predictive indices, the results were compared to the current standard benchmarks, and to the visual diaries' observed responses.
- Predicted vote for each participant was plotted as time-series. As predicted vote varies, the associated diary's images at the time of the change, and 5-minutes prior and posterior to the change were reviewed. Then the cause of the change in predicted vote could be identified.

Finally the results of the feedback interviews were reviewed, and the practicalities associated with the methods employed assessed, in particular how intrusive was the equipment on everyday life.

5.3.2.1 Reported and predicted information

During the first visit, participants were asked to assess the surrounding thermal environment at the time of the questionnaire. This assessment included their thermal perception, thermal preference, and affective assessment. Results show that participants' perception ranged from feeling '*slightly cool*' to '*warm*'; their preference ranged from desiring it to be '*slightly cooler*' to '*slightly warmer*'; and their affective assessment ranged from feeling '*comfortable*' to '*slightly uncomfortable*'. When comparing thermal perception and preference, the participants feeling '*slightly cool*' wanted to be '*slightly warmer*', however some participants feeling '*slightly warm*' and '*warm*' did not want to change as shown in Figure 5.8. When comparing thermal perception and affective assessment, most participants feeling '*slightly cool*' and '*warm*' felt '*slightly uncomfortable*', as shown in Figure 5.9. Therefore it would appear that participants are prepared to tolerate sensations of warmth but not cold.

Perceived thermal comfort was compared to predicted thermal perception derived from the current standard using the ISO 7730:2005 PMV model. In order to use this index, the six input variables were ascertained as follows:

- Indoor air temperature and relative humidity were monitored using an Onset HOBO U12-012 datalogger placed next to the respondent at the time of the survey. Recorded temperature ranged from 16 to 24 °C, while relative humidity ranged from 40 to 65%, as shown in Figure 5.10.
- Relative air velocity was not measured during the pilot study; instead a minimum air velocity of 0.1m/s was assumed for all cases on a basis that in winter openings tend to stay closed (Hong, S. et al., 2009).

- Mean radiant temperature was not measured as part of the pilot study; instead it was assumed that it was of equal value to the monitored air temperature as the velocity was assumed to be below 0.15 m/s (ISO 7726:2001). Moreover previous studies found that radiant temperature does not vary significantly from air temperature within homes (Ose-land, N. and Raw, G., 1991).
- Clothing and activity levels were estimated from the participant's answers to the questionnaire, using the ISO 7730:2005 checklist. Clothing ensemble levels ranged from 0.5 to 1 clo; while respondent activity levels during the questionnaire varied from 1 to 1.5 met. Some participants were seated while others carried out light activities.

Figure 5.8: Distribution of reported thermal perception and thermal preference votes for all pilot study's participants.

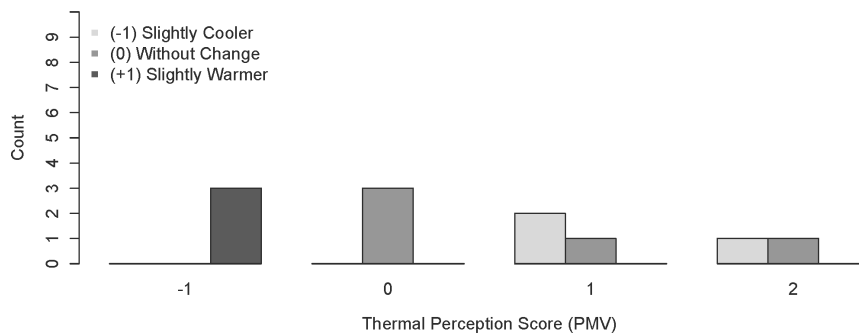
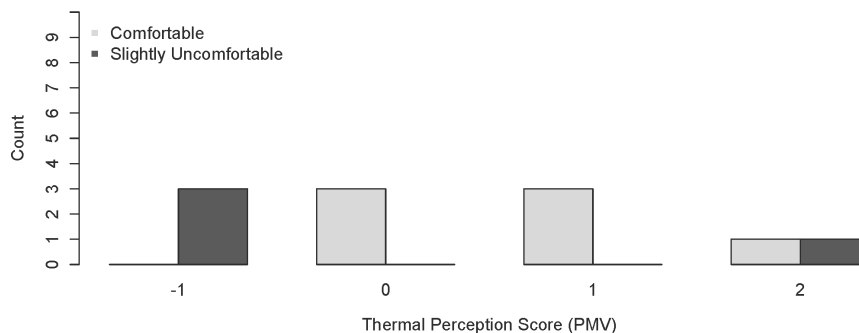


Figure 5.9: Distribution of reported thermal perception and affective assessment votes for all pilot study's participants.



Following these methods of estimation, Figure 5.10 shows the distributions of indoor air temperature, relative humidity, thermal insulation and metabolic rate.

Figure 5.10: Distributions of environmental and personal variables' levels for all pilot study's participants at the time of the questionnaire.

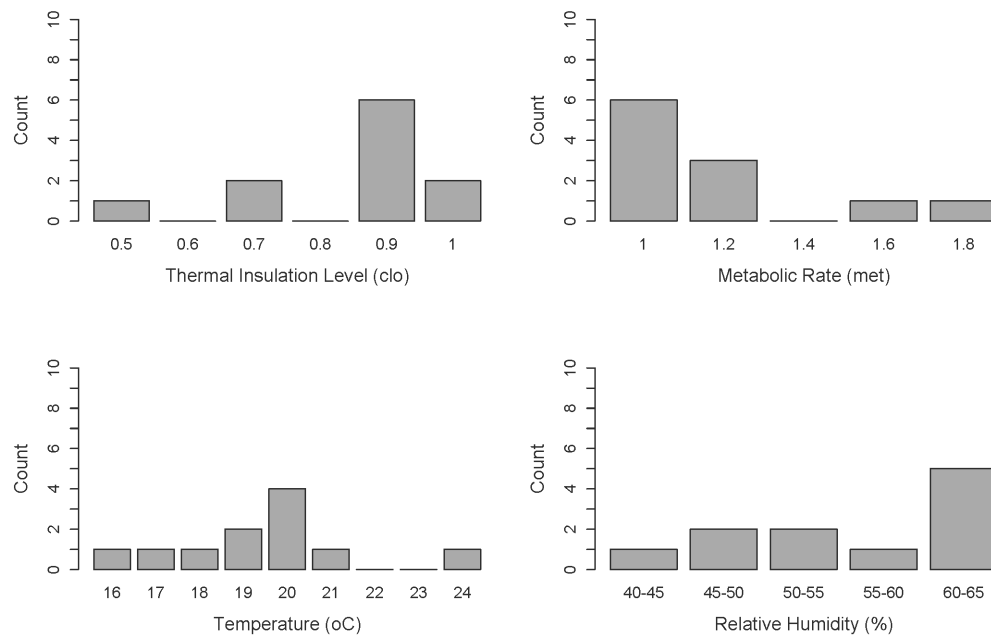


Figure 5.11: Reported and predicted thermal comfort vote during the pilot study's questionnaire.

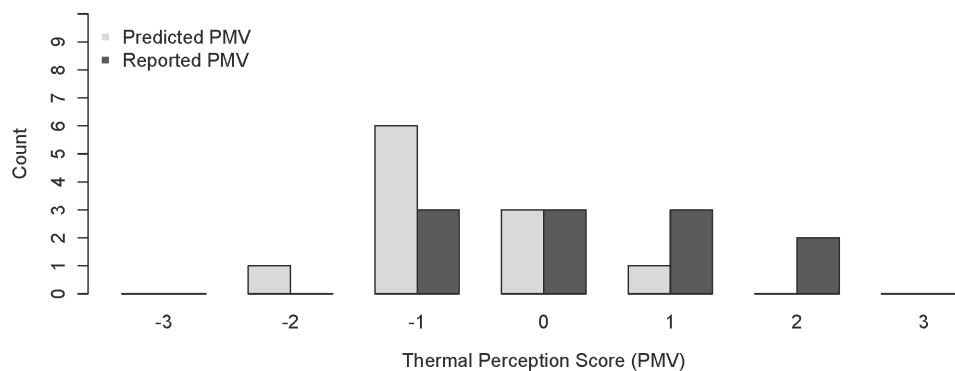


Figure 5.11 compares all participants' self-reported comfort votes in questionnaire A, and their predicted votes calculated from monitoring and questionnaire results. Mean predicted thermal comfort was equal to -0.55 ± 0.81 , and reported thermal perception equal to 0.36 ± 1.12 .

This comparison suggests that mean predicted thermal comfort was lower than mean perceived thermal sensation by an average of 0.9 units. This result is similar to the findings of Oseland, N. (1994). If the predictive model was used to control the heating system, the required set-point may be over estimated. Also to follow Hong, S. et al. (2009) reasoning, the assumed low air speed of 0.1 m/s can not explain the discrepancy between the two scores, as greater air speed would have resulted in even lower predicted votes.

5.3.2.2 Reported and observed information

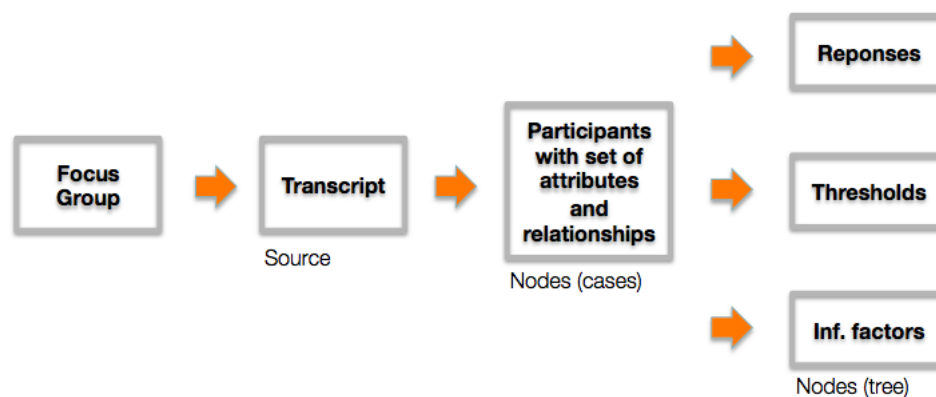
Reported information from the focus group

Using content analysis, focus group's transcripts were first coded by case nodes, defined by the participants' set of attributes. Then a portion of the text was attributed to each participant. Finally to follow the discussion's guide themes, the transcript was then coded using three nodes, defined as:

- Reported responses to cold thermal discomfort.
- Personal thresholds and triggers, defined as the time it takes to act when feeling cold, and what are the potential triggers i.e. shivering, 'bleu' fingers, temperature display, sounds of the wind or rain, etc.
- Influencing factors, including other occupant(s), previous experiences, personal or financial drivers, etc.

The analysis process is summarised in Figure 5.12.

Figure 5.12: Pilot study focus group coding sequence using Nvivo v7.



As illustrated in Table 5.2 and Figure 5.13, the results of this analysis show that the most likely responses to cold thermal discomfort for the sample group are:

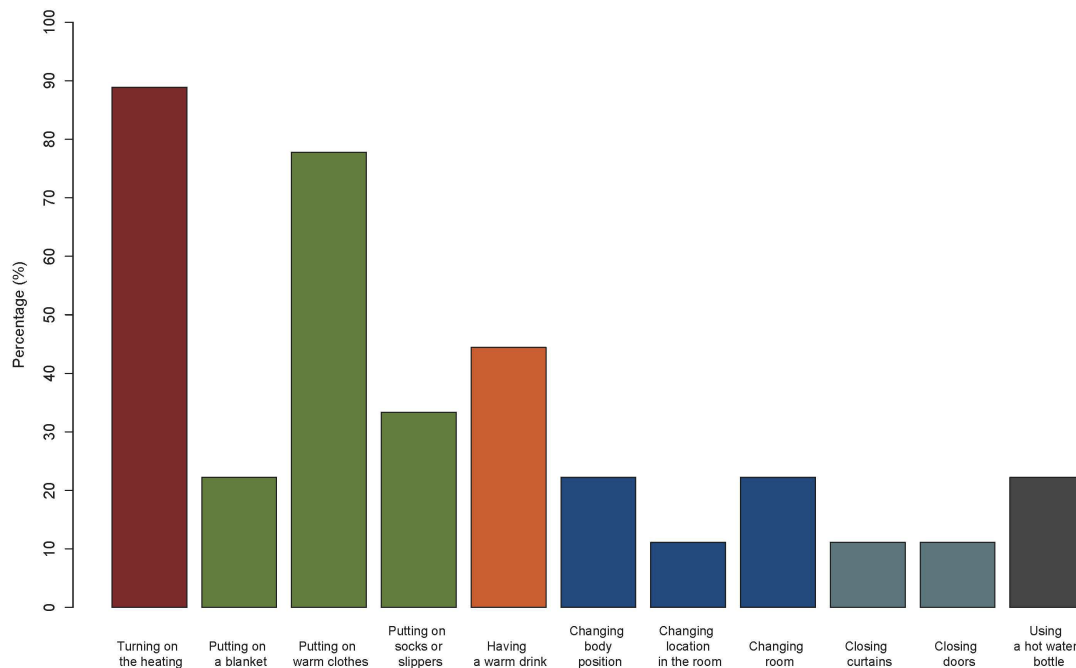
- Interacting with the heating system via TRVs, room stat or programmers (44%).
- Layering as putting clothes on or off, thermal insulation (38%).

Interestingly, the influencing factors to thermal discomfort were varied, and included 14 themes. This suggests that home thermal comfort systems may not be restricted to the dwelling's mechanical system but include friends and family, neighbours and household characteristics.

Table 5.2: Summary of the pilot study focus group results

Responses		Thresholds		Influencing factors	
no. of accounts: 50		no. of accounts: 10		no. of accounts: 43	
Heating	44%	Cold feet	50%	Friends and family	28%
Clothing	38%	Draughts	30%	Neighbours	19%
Food and drinks	12%	Cold hands	20%	Dwelling characteristics	16%
Blanket	10%	Shivering	10%	Outside environment	7%
Changing room or location	8%			Clothing	2%
Windows or doors	6%			Activity	2%
Hot water bottle	6%			Energy conscious	2%
Body position	4%			Cost of energy	2%
Shoes	2%			Upbringing	2%
Blinds	2%			Natural preferences	2%
				Habits	2%
				Expectations	2%
				'homely'	2%
				Sensation 'visual'	2%
				Sensation 'draught'	2%

Figure 5.13: Pilot study focus group results.

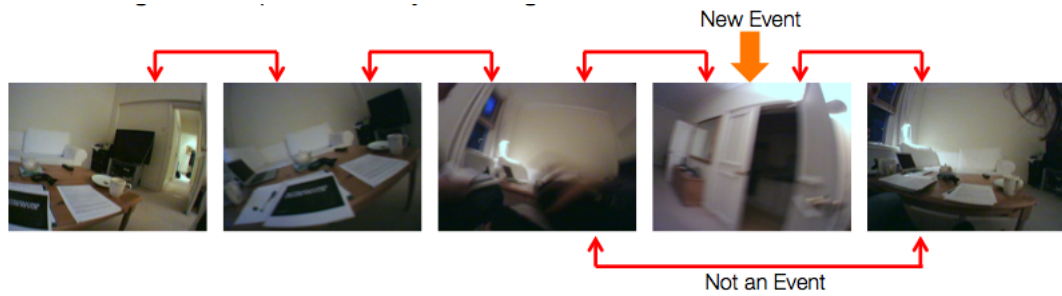


Observed information from the visual diary

Throughout the visual diary collection, the SenseCam device captured up to 6,300 images per participant. This yields a very large collection of images and extensive amount of information. To process this data, two approaches were used, first manual segmentation followed by automatic segmentation (Doherty, A. and Smeaton, A., 2008) (Byrne, D. et al., 2010).

Similar to content analysis techniques, the first step in manual segmentation of visual diary consists in examining each picture, and associate it to pre-established themes. To label each image, a list of themes was determined and included the following: image number, when and where the image was taken, how many persons where in the room, clothing and activity patterns. The second step consisted in reviewing the images sequentially for each participant. Adjacent images were compared, if a change in themes occurred, a new event was identified. This process is illustrated in Figure 5.14. To test this analysis method, manual segmentation step one and two were used to analyse the visual diary of participant 01 (P01). The results consisted in identifying 16 events of which '*living room & standing-up*' was the most frequent with 18% of all accounts, followed by '*kitchen & standing-up*' with 17% of all accounts, and finally '*living room & seated & laptop*' 11% of all accounts. In summary this process was time consuming, but allowed to log participants' activity and clothing level throughout the monitoring period of three days.

Figure 5.14: Pilot study manual event segmentation process.



To answer some of the limitations of the manual segmentation, an automated process was tested. After uploading the images, these were automatically processed using a software developed by Dublin City University (DCU) (Hodges, S. et al., 2006) (Lee, H. et al., 2008). It uses content-based image analysis techniques to structure the images into a list of events, referred to as index. The automatic segmentation technique was carried out in three stages:

- Stage 1: the images' visual features were identified, and grouped by association. These features included scalable colour, edge histogram, colour structure and moments.
- Stage 2: each group of images were compared with sensors' output log, including light level, temperature and acceleration. From this process different themes emerge i.e. indoor or outdoor, location in the building, eating/drinking, etc.
- Stage 3: the accelerometer output is reviewed to determine if the participant is static or moving, or if the camera is static.

Using this approach, 22-events were identified for participant 01. The results of this analysis were less successful than the manual segmentation, as the nature of the event was repetitive and not representative of the participants' activity. Further work may need to be carried out for this segmentation approach to be reliable, starting with the image clustering and reviewing the threshold level for each sensor log output.

5.3.2.3 Observed and predicted information

Indoor temperature and relative humidity

External dry-bulb temperature and relative humidity were monitored throughout the pilot study using Onset HOBO U12-012 dataloggers. These were located in central London, and had a sampling rate of 5min. The results were used as an indicator of whether the external temperatures were low enough to require space heating. As external temperatures were below 15.5°C

for 95% of the recording period, CIBSE winter environmental design criteria were used as benchmarks (2006); summarised as:

- Indoor temperature: living rooms [22-23°C], kitchens [17-19°C] and bedrooms [17-19°C] (Table 1.5).
- Indoor relative humidity: 30 to 70% (Section 1.3.1.3).

Indoor monitored temperatures were compared to these benchmarks, the results are summarised in Figure 5.15 and Figure 5.16. Results show that 70% of recorded temperatures were outside CIBSE benchmarks; on the other hand 92% of recorded relative humidities were within the benchmark. These results are surprising as 89% of temperatures recorded in living rooms were below 22 °C. However in bedrooms, 49% of the recorded temperatures were above 19 °C. Over the three days of monitoring, the mean living room temperature was 19.1 ± 2.2 °C, and the mean bedroom temperature was 19.2 ± 1.8 °C, which is similar to the finding by Oseland, N. (1994) with mean air temperature set at 19.2 ± 2.2 °C. With regards to mean relative humidity, the mean living rooms' recordings was 57 ± 7 % , while the mean bedrooms' recordings was 58 ± 9 %, which is again similar to the findings by Oseland, N. (1994) with mean relative humidity set at 57.4 ± 12.4 %.

Figure 5.15: Internal monitored temperature and relative humidity in living rooms during the pilot study, with CIBSE benchmarks highlighted (grey-box).

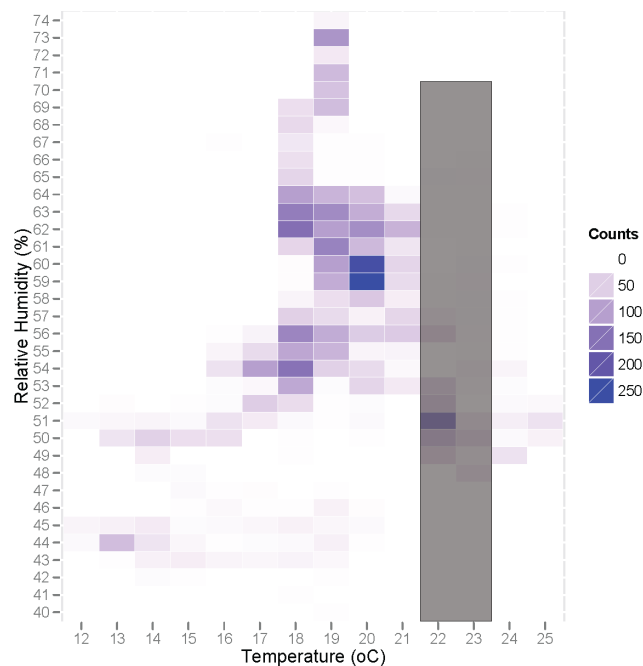
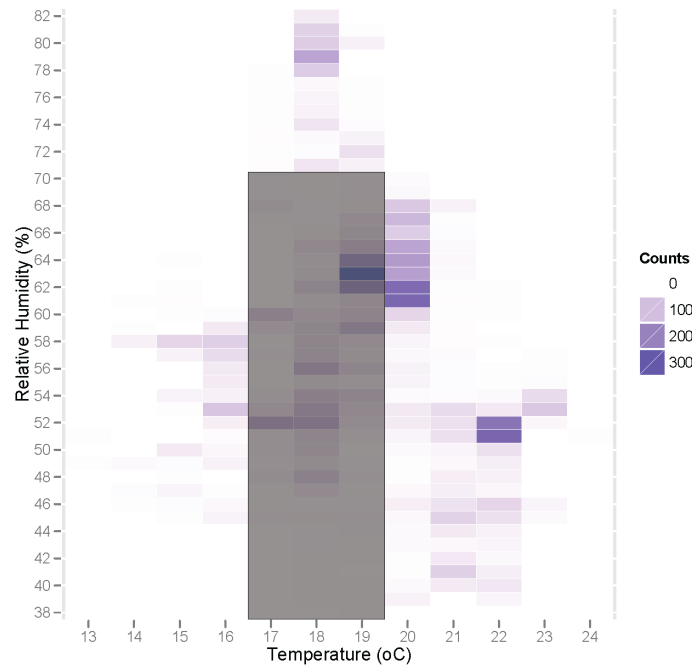


Figure 5.16: Internal monitored temperature and relative humidity in bedrooms during the pilot study, with CIBSE benchmarks highlighted (grey-box).



Predicted thermal sensations

As external temperature was below 15.5°C for most of the monitoring period, only the predictive approach may be applied. The predicted thermal sensation of each participant was calculated using the ISO 7730:2005, Annex D. These estimations were made at 5-minutes intervals when the SenseCam was worn. The 6-input variables were ascertained as follows:

- Environmental variables; the same estimation methods as the one used during the questionnaire were applied. Air temperature and relative humidity were monitored using dataloggers. Mean radiant temperature was assumed to be equal to air temperature, and relative air velocity was assumed to be equal to 0.1m/s. Participants' locations in their dwellings were established by the analysis of the visual diary, thus the predicted models' inputs were specific to the rooms where the participants were located.
- Personal variables; activity and clothing level were ascertained using the results of the visual diary manual segmentation.

The boxplots in Figure 5.19 show the variability of predicted thermal sensation for each participant throughout the monitoring period. Overall, the mean PMV for all participants was -0.9 ± 0.5 . This analysis revealed that most participants should be feeling '*slightly cool*' to

'cool' for most of their time at home. In fact 77.5% of calculated PMV during occupied time was outside of the bound of ISO 7730:2005 category B, set at $-0.5 < \text{PMV} < +0.5$, as shown in Figure 5.17. With regards to predicted percentage of dissatisfied (PPD), only 20% of the occurrences were within ISO 7730:2005 category B, set at $\text{PPD} < 10\%$, as shown in Figure 5.18. Overall, the mean PPD for all participants was $26.5 \pm 19.8\%$.

Figure 5.17: Predicted mean vote for all participants throughout the monitoring period, with ISO 7730:2005 categories A, B, and C highlighted as dotted lines and the bound of category B in orange box.

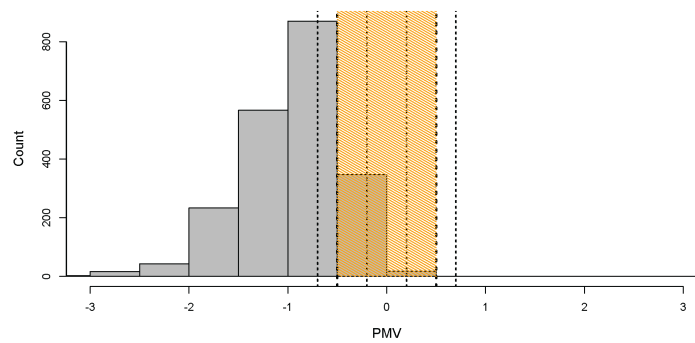


Figure 5.18: Predicted percentage of dissatisfied for all participants throughout the monitoring period, with ISO 7730:2005 categories A, B, and C highlighted as dotted lines and the bound of category B in orange box.

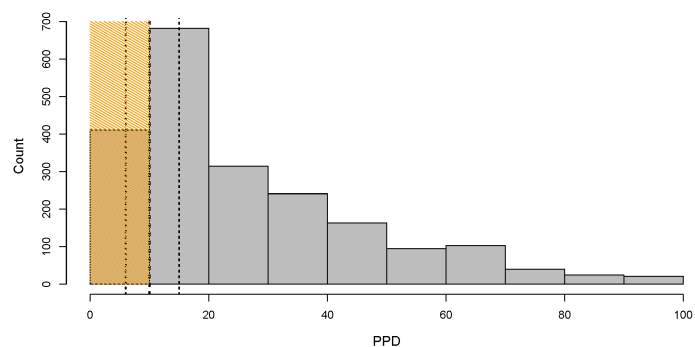
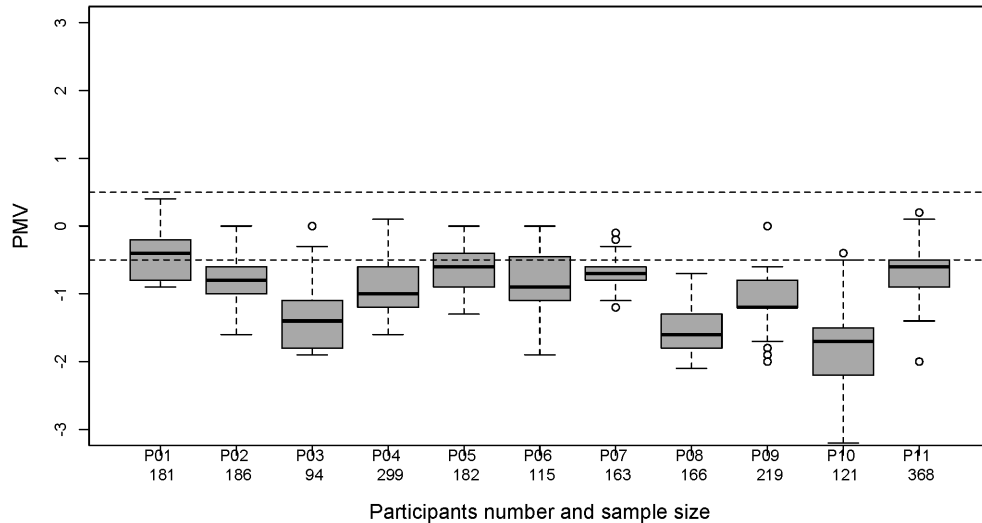
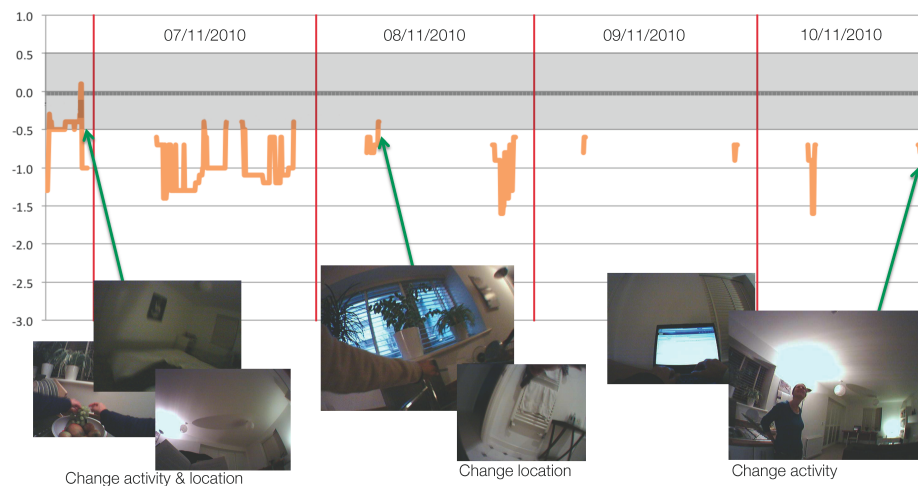


Figure 5.19: Predicted mean vote for each participant throughout the monitoring period, with ISO 7730:2005 categories B highlighted as dotted lines.



Finally, differences between predicted thermal sensation of the sample frame characteristics were reviewed. First the normality of each group was assessed using Shapiro-Wilk test, results show that none of the groups were normally distributed (p -value < 0.1). Then Kruskal-Wallis rank sum test was used to assess the difference between the groups. In summary, there was no significant statistical difference in means between either the two genders, age groups, weight, employment status, tenure status or between energy efficiency ratings (p -value > 0.05). These results may be due to the small sample size.

Figure 5.20: Observed responses and predicted vote compared



Observed responses and predicted vote

Predicted thermal perception (PMV) was plotted as a time-series, and when changes occurred images from the visual diary were reviewed. An example of this analysis is shown in Figure 5.20. This allowed the exploration of reasons that may have caused variations in PMV. In most cases, these variations were the results of changes in location within a room, changes of room, or changes of activity (for example cooking). Although this method allowed to reveal interesting insights, these source of change in PMV may not all be direct responses to cold thermal discomfort, but part of 'routines', for example a participant may decide to move to another room to carry-out a specific task (i.e. watching television or reading).

5.3.2.4 Review of the feedback interviews

At the end of the monitoring period, and during the second visit a feedback interview was carried out with the participants. The topics discussed may be grouped as follows:

- *Taking part.* Overall participants were very interested in the use of wearable sensors. For half of them, this was described as the reason for participating in the study; while for the other half, it was to explore how their home '*performed*' in winter. In particular investigating the indoor temperature levels in different rooms.
- *The instrument.* All participants were satisfied with the SenseCam, they did not encounter any practical issue, and found the control options straightforward. Only few participants had to re-set the device; then they referred to the user-guide. In all cases this was performed correctly, as all monitoring data were synchronised in the analysis.
- *Failing to wear the device.* Most participants forgot to wear the device at least once when returning home. This was in some instance recorded by the participant. The first part of the analysis was to draw a schedule of when the SenseCam was turned on and off. This allowed to review patterns of use, and uncover missing data. For example, when the device was switch on, the visual diary showed where this occurred and the activity carried out. This confirmed that sometime participants forgot to wear the SenseCam when returning home.

- *Privacy.* Most participants did not have privacy concern. Only one participant asked to review all the pictures one-by-one before being handed over to the researcher. This was straightforward; during the second visit the SenseCam's data were downloaded and the pictures reviewed by the participant, who deleted some sections. Another participant noted down the sections of time to be deleted, this was also done during the second visit and in the presence of the participant.
- *Hawthorne effect.* Most participants reported feeling less self-conscious of wearing the SenseCam after the first hours or first day of use. Only one participant reported to have changed his/her behaviour in response to the awareness of being observed. This participant reported being more sedentary and stayed in the living room for most of the monitoring.
- *Duration.* Most participants felt that 3-days was not enough to capture all their different responses to cold thermal discomfort, and suggested longer monitoring periods, from one week, up to one month.

The insights from this feedback interview were very valuable when establishing the research design of the main study. In particular the monitoring period was extended to 10-days. Also the first monitoring day was regarded as an '*adaptation period*', and was not taken into account in the analysis.

5.3.3 Summary of the pilot study

The aim of this pilot study was to assess the validity and limitations of current standards and emerging methods using ubiquitous sensors. Firstly, a comfort survey was carried out. Results show that the predictive approach tends to underestimate thermal sensation. Then a monitoring study was carried out for three-days, results show that the mean PMV for entire samples was below ISO 7730:2005 category B threshold. Additionally, the mean living room temperature was below CIBSE guide A benchmark for most of the occupied time period.

With regards to mapping participants' cold thermal discomfort responses, the focus group allowed a list of reported responses to be gathered. The most frequent being *interacting with the dwelling's heating system*, followed by *putting on/off items of clothing*. These two themes are similar to the one found by Burris, A., Mitchell, V. and Haines, V. (2012) in a series of interviews. To follow on from this analysis, the output of the visual diary was reviewed using manual and automated segmentation techniques. The manual segmentation allowed the estimation of clothing and activity levels throughout the monitoring period. These results were then used as input to the predictive model. On the other hand, the outcomes of the automated

segmentation were inconclusive. As a manual segmentation method is time consuming and prone to observer bias, the main study should aim to develop a new automated segmentation approach. Besides, the pilot study has highlighted the following limitations:

- Sample: non-probability, small. Recruitment of participants remains a barrier due to the amount of monitoring. For this reason the main study should identify an explicit sample frame, and recruit participants within these boundary conditions.
- Response bias: The focus group results may be influenced by group-effects where participants' opinions may be prone to culturally expected views rather than individual ones; and moderator-effects where participants feel the need to please the moderator.
- Location: London, UK, temperate climate. The results may differ for other countries, nonetheless the set of methods used may apply elsewhere.
- Season: winter, heating season. It is expected that there may be some divergence between seasonal results.

To conclude, this empirical study has suggested directions to monitor people's responses to thermal cold thermal discomfort. It has also outlined the various considerations that need to inform the planning process of the main study by describing in some detail the responses types. This study has also highlighted the importance of referring to existing methods of data collection and classification.

5.4 Main study - results and analysis

In light of the results of the pilot study, the aim of this study was to gather and to analyse people's responses to thermal discomfort in dwellings during the heating season. In particular, the objectives of the main study are as follows:

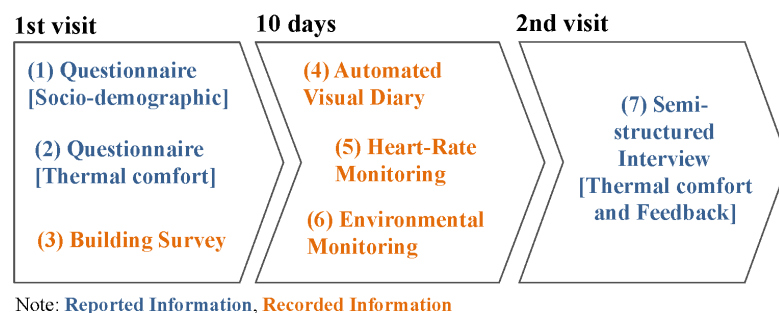
- To identify a sample frame and associated set of case studies, and to carry out the field study (data collection).
- To collate this data in a comprehensive database (data processing).
- To develop an analysis method that will identify reported, observed and predicted responses to thermal discomfort (data analysis).
- To identify the variation of observed behaviour and predicted thermal comfort in time (data analysis).

To complete these objectives, the main study employed standard methods to collect benchmark parameters, and novel methods using ubiquitous sensors. The study was carried-out over two winter seasons in 2012, from January to March and from October to December. It is the same study that was used in Chapter 4. This section will first introduce the study design, then results will be analysed and discussed.

5.4.1 Study design

The study was carried out in the South-East of England, over two winter seasons in 2012. Using convenience sampling, 20-participants living in 19-different dwellings were monitored over a minimum period of 10-consecutive days. The data collection sequencing is summarised in Figure 5.21.

Figure 5.21: Individual case study data collection sequencing used for the main study.



5.4.1.1 Sampling frame and sampling strategy

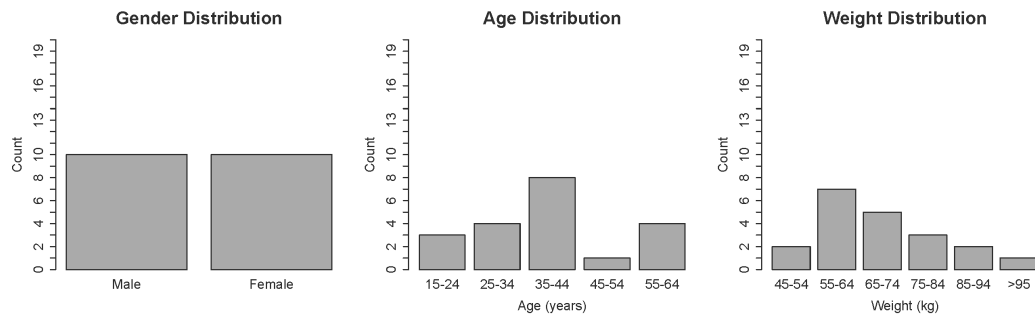
Results of the sensitivity analysis in Chapter 4 show that the most influential variables in standard predictive models are the two personal variables, metabolic rate and the thermal insulation of clothing. In current field studies, the values given to these two variables are usually estimated from observations (de Dear, R., Brager, G. and Cooper, D., 1997). These estimations hold great uncertainty. Consequently, it is critical to be able to determine those factors with greater precision and accuracy. As reviewed in chapter 4, metabolic rate can be determined from accelerometry or recordings of the subject's heart-rate. While applying these methods the sampling frame may be defined by the 3-physiological attributes prescribed by ISO 8996:2004 Annex C, as gender, age and weight. Using a convenience sample, the participants were selected within this sampling frame, see Figure 5.22 and Figure 5.23. Although this sample is not representative of the UK population, it provides insights to answer the aims of this study.

Figure 5.22: Pilot study sample frame - Physiological characteristics (EN ISO 8996, Annex C).

Age (years)	Weight (kg)				
	50 kg	60 kg	70 kg	80 kg	90 kg
Women					
20	P01				
30		P02, P09	P07		
40		P03, P10, P17			
50					
60	P14		P19		P16
Men					
20		P05	P04		
30			P06		
40		P18		P08, P20	P11, P13
50				P12	
60			P15		

Within the sample group, most participants were working part-time (7 participants), or in full-time education (7 participants). Others were either working full-time (4 participants), retired or at home not seeking work. About half of the participants were owner occupiers and the other half were renting. Located in the South-East of England, the dwellings were built in different periods, dating from 1850 to 2008. Twelve dwellings were terraced, four were within apartment-blocks, three were detached, and one was semi-detached. The dwelling energy efficiency ratings ranged from category B to E, with most houses achieving a D rating (11 dwellings). Some incorporate features such as retrofitted central or communal heating systems. Only one dwelling was mechanically ventilated, all the other dwellings were naturally ventilated.

Figure 5.23: Main study sample frame - Physiological characteristics distributions.



The main study was carried out from the 27th of January to the 17th of March 2012 (7-weeks, part 1), and from the 26th of October to the 19th of December 2012 (8-weeks, part 2). During these 2-periods, the mean external temperature was $6.0 \pm 4.1^\circ\text{C}$ for part 1 and $6.7 \pm 3.1^\circ\text{C}$ for part 2. The mean external relative humidity was $78.4 \pm 8.2\%$ for part 1 and $83.1 \pm 5.6\%$ for part 2 (See Figure 5.24 and Figure 5.25). These external hygrothermal conditions originated from an open-source database, Wunderground. The recordings were taken every 30-minutes at London City Airport (Station ID: EGLC) (Wunderground, 2014). During these two periods, external temperatures were for 99.6% of the time below the degree-day threshold of 15.5°C , and low enough to require space heating (Chartered Institution of Building Services Engineers (CIBSE), 2006).

Figure 5.24: Main study part 1: Mean external relative humidity, and external temperature profile as minimum, mean and maximum values for each monitoring days. The degree day threshold of 15.5°C is identified by a dotted line.

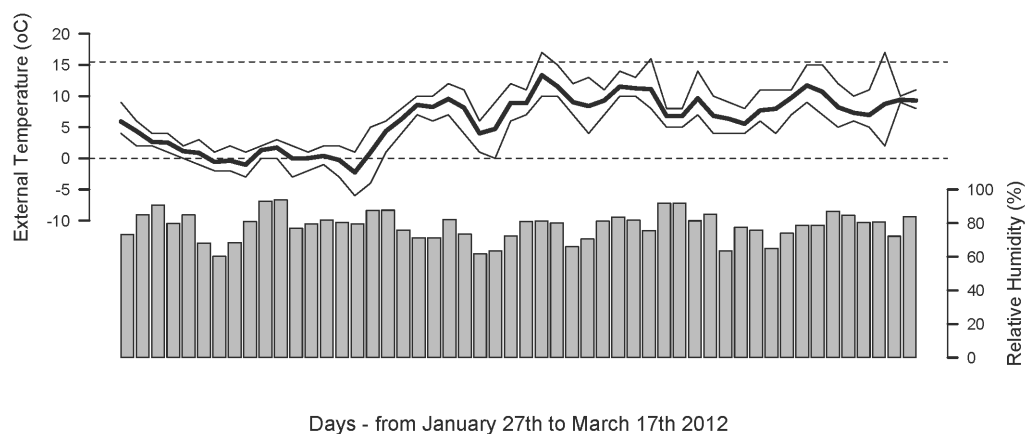
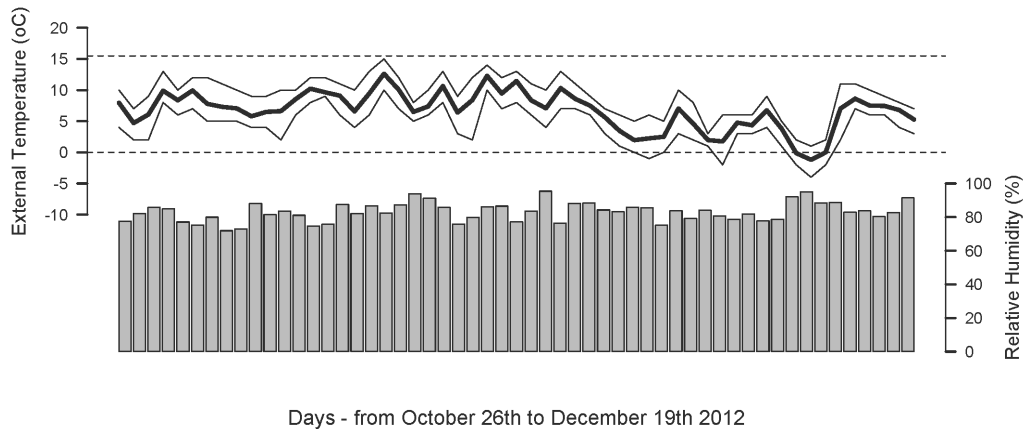


Figure 5.25: Main study part 2: Mean external relative humidity, and external temperature profile as minimum, mean and maximum values for each monitoring days. The degree day threshold of 15.5°C is identified by a dotted line.



Similar to the pilot study described in Chapter 5 Section 3 and as reviewed in the study design in Chapter 3, informed consent was sought from each participant to audio record the interview, and carry out a visual diary. Confidentiality was insured using name coding. All data was only reviewed by the researcher and two supervisors.

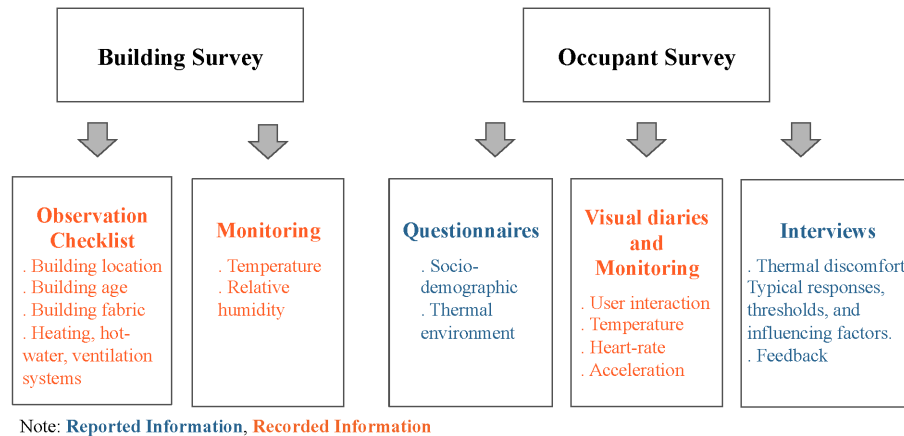
5.4.1.2 Mixed methods framework

The purpose of the monitoring study was to collect sufficient data to address the research question and objectives. Following the results of the pilot study, six collection methods were selected. This mixed methods approach enabled the collection of a wide range of information, which can be compared to current benchmarks and other studies. The methodological framework used for the main study is illustrated in Figure 5.26.

Questionnaires

Along the same lines as the pilot study, two questionnaires were completed with the participants during the first visit. Questionnaire A focused on the subjective assessment of the thermal environment, while Questionnaire B collected information on the participants' socio-demographic characteristics, and on the property (see Appendix A). Both questionnaires used established templates in ISO 10551:2001, ASHRAE 55:2013, ISO 7730:2005, RP-884 survey (de Dear, R., Brager, G. and Cooper, D., 1997), and Survey of English Housing (National Centre for Social Research (NatCen), 2007).

Figure 5.26: Main study methodological framework.



Building survey

Along the same lines as the pilot study, a building survey was completed during the first visit using RdSAP worksheet version 9.83 (BRE, 2012). This enabled the collection of information such as built form, age band, property layout, fabric type, heating, ventilation and hot-water systems.

Environmental sensors monitoring

The environmental monitoring was undertaken for a minimum period of 10-consecutive days. Three sets of 4-dataloggers were placed in living-rooms and in bedrooms to record ambient air temperature and relative humidity. These devices were programmed to start 30-minutes before the interview, and recorded a reading every 5-minutes. The sets of 4-dataloggers were fastened to a series of wooden-poles and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by EN ISO 7726:2001. Following the building survey, the three wooden-poles were positioned according to the room layout (cold/warm places), away from potential heat sources, and near the most likely occupied spaces. Their final positions were agreed with the participants to ensure minimum disruption. In addition air velocity was measured during the first visit using a hot-wire anemometer (Testo 425). Measurements were taken in different locations, depending on how the house is laid-out and lived-in. The results of this monitoring were used to calculate predictive indices for each participant throughout the 10-days period.

Visual diary

Along the same lines as the pilot study, a SenseCam was handed out to each participant during the course of the first visit. The visual diary was undertaken for a minimum period of 10-consecutive days. This wearable recording device took photographs when triggered manually and automatically by timer or by changes in sensors readings. If the participants needed to reset the device or wanted to record a specific event, the manual shutter button was activated. Also if they wanted to stop taking picture for a period, the privacy button allowed pausing of recording. In total 146,284 pictures were generated, which represents an average of 7,314 images for each participant. These pictures enable participants whereabouts to be mapped, in particular their food and drink intake, their activity and thermal insulation levels.

Heart rate monitoring

In addition to the SenseCam, a Kalenji heart rate monitor and associated user-guide were handed out to the participants during the first visit. This device is formed of 2-parts, a chest strap and accompanying logger. The research showed the participant how to wear the device, and how to turn it on/off. The chest strap needed to be placed near the heart, and the electrodes on either sides of the logger in contact with the skin. Occasionally these electrodes needed to be dampen with water to improve conductivity. Once the chest strap in place, it was paired via bluetooth with the logger, and started recording. The study asked for the participant to wear the heart rate monitor for a minimum period of 3-days, and concurrently to the SenseCam. Similar to the guidance given for the SenseCam (described in Section 5.3.1.2), the participants were asked to wear the heart-rate monitor only at home, from waking-up in the morning until going to bed at night, and to take it off when going out. The minimum monitoring period was set by the storage capacity of the device. Once turned on, a record was taken every 10-seconds. As the study's temporal unit of analysis was set at 1-minute, the heart-rate readings were average over 1-minute epoch. The recorded heart rate was then used to evaluate participants' activity level, as described in Chapter 4.

Semi-structured interview

Ten days after the first visit, the researcher returned to the dwelling to collect the equipment, and to conduct a semi-structured interview with the participant. The aim of this interview was to gather feedback on the monitoring methods, and gather accounts of their behavioural responses toward thermal discomfort. Open-end questions addressed typical responses, associated thresholds and influencing factors. The analysis of the transcripts used content analysis.

5.4.2 Results

Along the same lines as the pilot study, the main study analysis framework consisted in the review of occupants' reported, observed and predicted information, defined as follows:

- Reported information includes direct accounts from the participants in the questionnaire and semi-structured interview.
- Observed information includes the output of the automated visual diaries and the wearable sensors.
- Predicted information includes environmental monitoring and measurements of activity and clothing levels as described in chapter 4.

To compare and contrast these three types of information, the analysis is structured in three parts, described as follows:

- Reported and Predicted responses. Results of the thermal comfort survey undertaken during the first visit are compared to predicted thermal sensation.
- Reported and Observed responses.
 - The results of the semi-structured interviews were used draw a list of reported responses to cold thermal discomfort. Concurrent automated segmentation identified respondents actual responses. These were then compared and contrasted.
 - Monitored activity and clothing levels were compared to internal temperature levels using regression analysis. The outcome was then compared to the semi-structured interviews results.
- Observed and Predicted responses.
 - Monitored indoor mean temperature and relative humidity were compared to the CIBSE environmental design criteria.
 - Monitored environmental and personal variables were used as input to the PMV model, the results were then compared to the current standard benchmarks.

Finally the results of the feedback interviews were analysed and assessed the methods, in particular how intrusive these were on everyday life.

5.4.2.1 Reported and predicted information

In the questionnaire survey, the participants were asked to rate their thermal perception, thermal preference, and affective assessment. Results shows that participants reported feeling '*slightly cool*' to '*hot*', as shown in Figure 5.27. Interestingly one participant felt '*hot*', and wanted to be '*slightly warmer*'. Having reviewed the questionnaire's entry and notes, this result was questioned during the interview. The participant confirmed feeling '*hot*' at the time of the interview, but the preference of being '*slightly warmer*' was referring to his/her general thermal preference while at home. The same interpretation was made by two participants feeling '*warm*'.

Figure 5.27: Distribution of reported thermal perception and thermal preference votes for all participants.

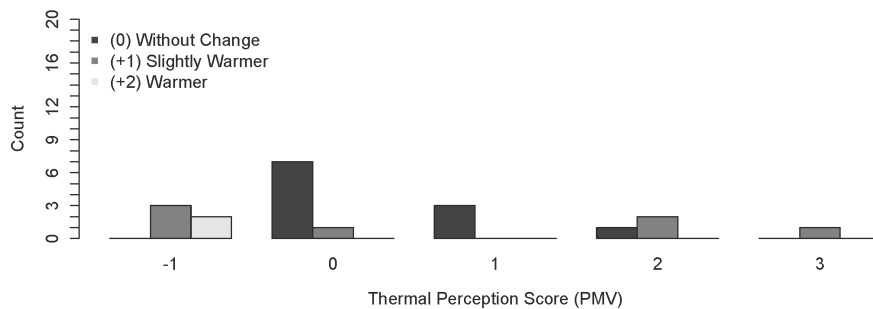
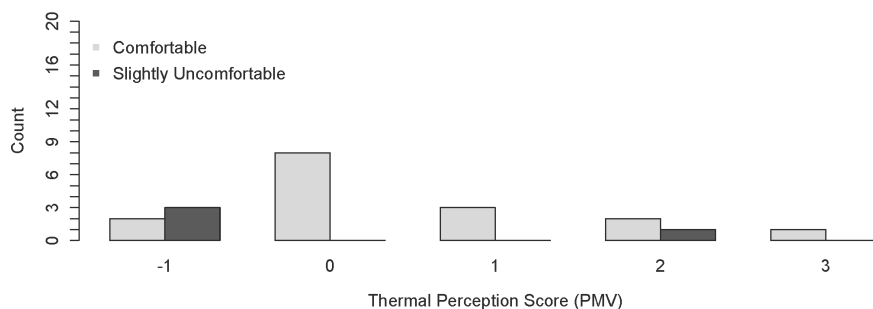


Figure 5.28: Distribution of reported thermal perception and affective assessment votes for all participants.



This analysis highlights the importance of cross-validation surveys, and the need for follow-up interviews. With regards to affective assessment, the participants feeling '*slightly uncomfortable*' were at either end of the thermal perception scale, as shown in Figure 5.28.

The participant feeling '*hot*' at the time of the interview, considered his/her home to be '*comfortable*'. As refer to in Brager, G. et al. (1993), this participant may want his/her home to be '*slightly warmer*', but it is still deemed '*comfortable*'; therefore an acceptable environment may not just be '*neutral*', but may range from been '*slightly warm*' to '*slightly cool*'. This stretches the band of comfort acceptability.

Participant's reported thermal comfort was compared to the predicted thermal perception, by applying the PMV model described in ISO 7730:2005. In order to use this index, the six input variables were determined as follow:

- Indoor air temperature and relative humidity were monitored using Onset HOBO U12-012 dataloggers placed next to the respondent at the time of the questionnaire. Results show that temperature varied from 15 to 22 °C, and relative humidity from 30to 65%, as shown in Figure 5.29.
- Relative air velocity was measured using Testo 425. For all participants, the results were below equal to or below 0.1m/s; therefore 0.1m/s was assumed for all cases.
- Mean radiant temperature was not measured as part of the study; instead it was assumed to be equal to monitored air temperature as air velocity was below 0.15 m/s (ISO 7726:2001).
- Activity and clothing levels were estimated using ISO 7730:2005 checklists in Annex B and C respectively. Activity levels ranged from 1 to 1.6 met, as most participants were '*seated and relax*', while other were standing and carrying out light activities. The clothing levels ranged from 0.6 to 1.3 clo, as shown in Figure 5.29.

Having estimated values to the six input variables, predicted thermal perception was calculated for each participants. Figure 5.30 compares all participants self-reported comfort votes in questionnaire A and their predicted votes computed from monitoring results. This comparison shows that predicted votes are lower, by an average of 1.6 units. This is similar to the findings in Oseland, N. (1994). The mean predicted thermal comfort vote was -1.21 ± 0.63 , while reported thermal perception was 0.35 ± 1.18 . The level of mean reported thermal perception is similar to the one reported in the pilot study, however the predicted comfort level is much lower (difference of 0.66 units).

Figure 5.29: Distributions of environmental and personal variable levels for all participants at the time of the questionnaire.

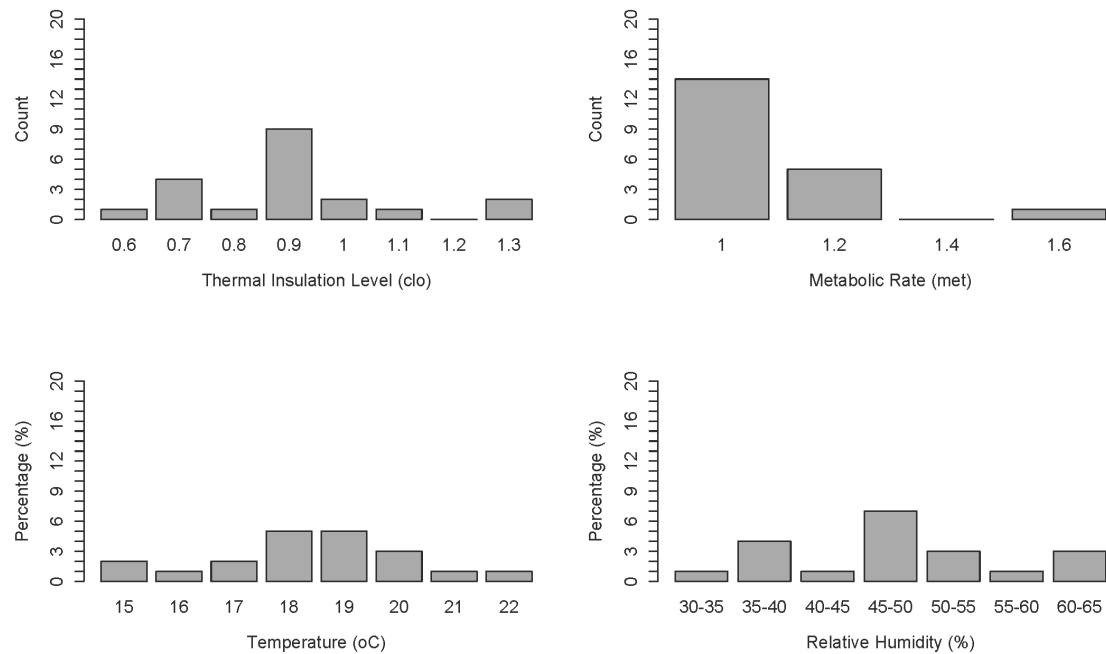
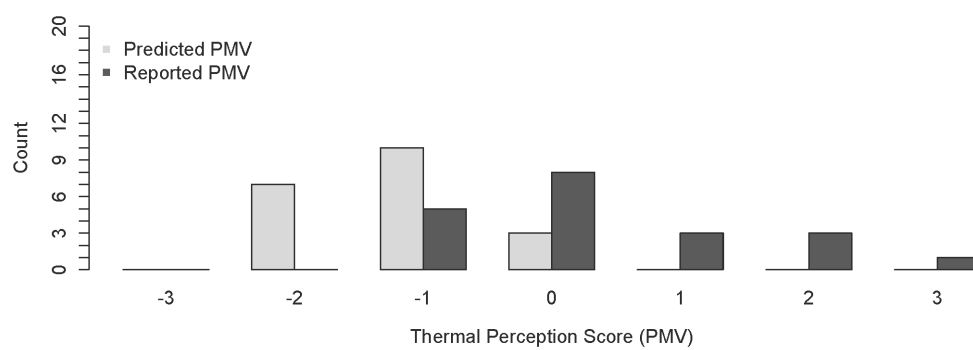


Figure 5.30: Reported and predicted comfort vote during the first visit of the main study.



5.4.2.2 Reported and observed information

Reported information from the semi-structured interview

Figure 5.31: Main study semi-structured interview results - reported responses to thermal discomfort.

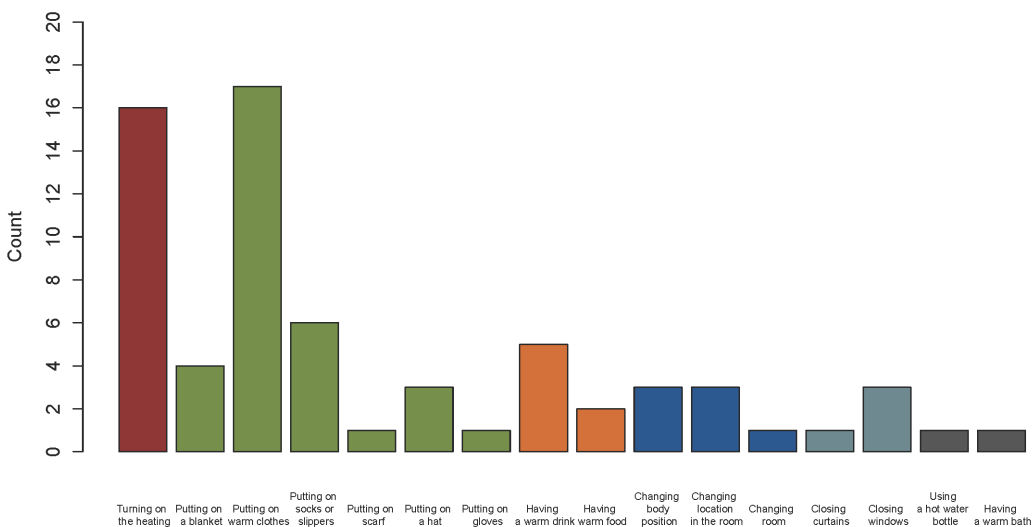
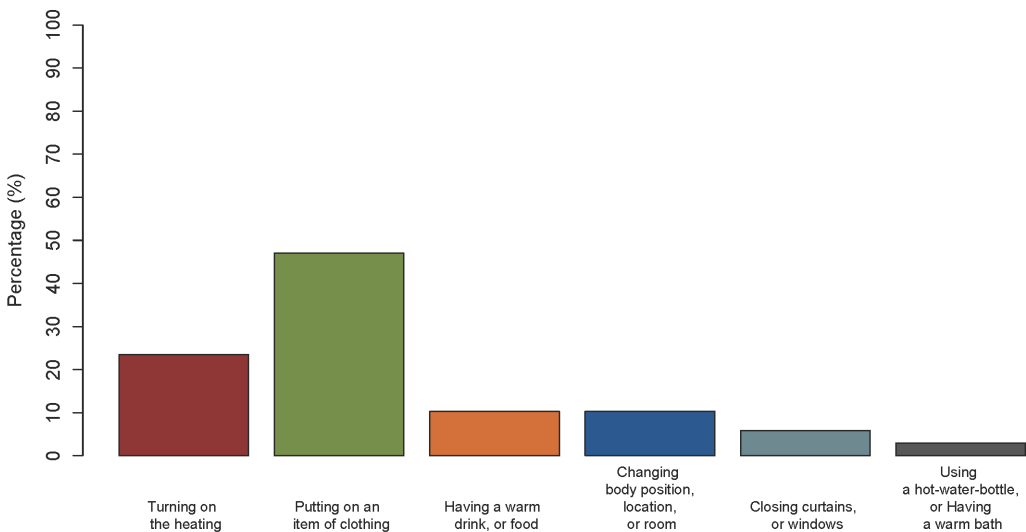


Figure 5.32: Main study semi-structured interview results - reported responses to thermal discomfort.



Along the same lines as the pilot study analysis of the focus group, content analysis was used to review the semi-structured interviews transcripts with discussion themes were used as nodes. These included typical responses, thresholds and influencing factors to cold thermal discomfort. As illustrated in Figure 5.31 and Figure 5.32, the results of this analysis revealed that the most common responses for the sample group are:

- Layering as putting clothes on, thermal insulation (47%).
- Interacting with the heating system via TRVs, room thermostat, or programmers (24%).

Interestingly these results are similar to the pilot study's reported responses. Moreover, two type of responses, '*having warm food or drink*' and '*using a hot-water-bottle or having a bath*', are currently not accounted for in standard models.

Observed information from the visual diary

The automated diary accounted for up to 24,306 images per participants, and an average of 7,500 images over a monitoring period of 10-days or more. This yields a very large collection of images, and an extensive visual diary. To process this information, automatic segmentation was used in a five step sequence:

- Formatting - After uploading the SenseCam data, the images and the output from the temperature sensor were extracted from the diary-log. This temperature entry gives an estimation of the temperature at the surface of the clothing on the participants' chests, and is refer to as T_{clo} expressed in degree celsius ($^{\circ}\text{C}$).
- Formatting - T_{clo} readings were then averaged over the chosen time-unit of analysis set as a 1-minute epoch.
- Normalising - While reviewing T_{clo} time-series profiles, temperature rises were observed each time a participant put-on the SenseCam. These artefacts are unwanted information contained within T_{clo} reading profiles. Prior to carrying-out the analysis, the profiles were reviewed and these artefacts discounted; this process is called normalising. The method consists in identifying the temperature rise-time due to the resistance of the device and/or to changes in the environment. To do so, a software filter was written which identifies the lagged differences between consecutive readings. The filter boundary condition was set to T_{clo} being stable during a 5-minutes period.
- Structured-query - Consecutive normalised T_{clo} readings were compared, and if those increased or decreased by 1°C or more, associated images were identified or more over

1-minute, associated images were reviewed at the time of the change occurring, and 5-minutes prior and posterior to the change. This was carried out to identify and validate associated behavioural-responses to change in T_{clo} .

Figure 5.33: Main study diary results - Observed responses.

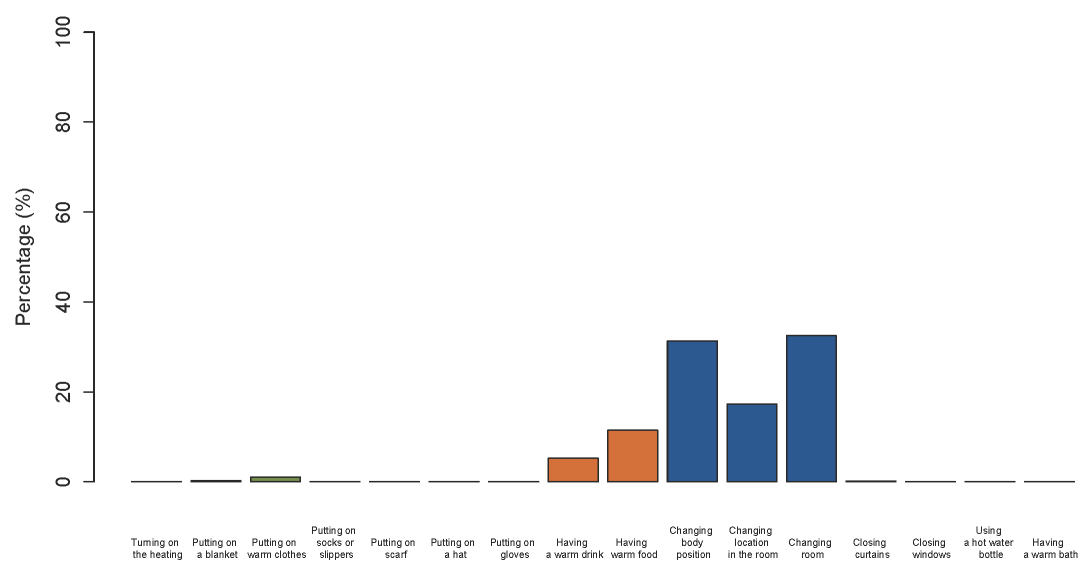
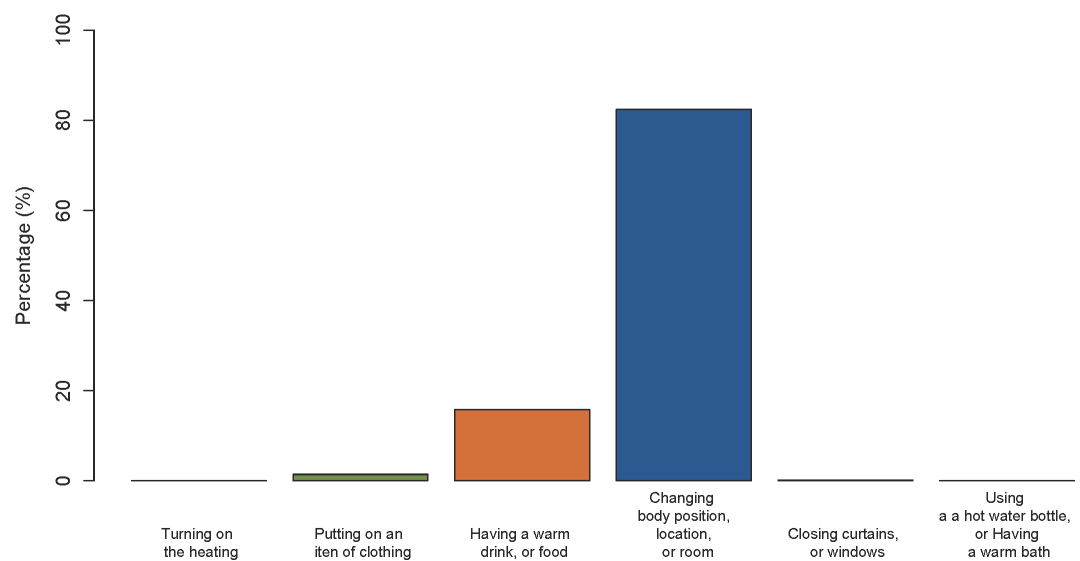


Figure 5.34: Main study diary results - Observed responses.



This structured data-query process enabled filtering of the images to those in close proximity to observed changes in T_{clo} making manual inspection of the remaining images possible. After processing approximately 15% of the original images remained making manual inspection of the remaining images possible. Inspection of the images then allowed for identification of the reasons for changes in T_{clo} . Through this approach participants responses to changes in T_{clo} were identified, and the results are summarised in Figure 5.33 and 5.34.

Interestingly, the frequencies of observed actions differ greatly to the reported responses. In this context, there are two important caveats that should be borne in mind in interpreting such visual diary data. Firstly, it is important to note that the localised behaviour responses observed in the SenseCam images are not necessarily, or even predominantly, thermal discomfort responses. Occupants move, consume hot food and drink, and change clothing for many reasons, thus, it is probable that the majority of the observed actions associated with "*Having a warm drink or food*" and "*Changing body position, location or room*" are not thermal discomfort responses, but arise from other causes. This poses a potential threat to the internal validity of the findings. Secondly, in multiple occupant households, others may undertake thermal comfort measures on the households behalf. These would not be recorded and could create missing data biases. To address these concerns, regression analysis between indoor monitored temperature (T_a) and the most frequently reported response (clothing insulation levels) and the most frequently observed response (motion), are carried out in the next section.

Review of the relationship between air temperature and the most frequently reported response - clothing level

Having estimated thermal insulation of clothing as a quantitative, objective, and continuous variable in chapter 4, its relationship with ambient temperature (T_a) may be evaluated using regression analysis. If participants were to always adjust their thermal insulation level by adding more clothing items as a response to colder temperatures, then the correlation coefficient should be close to -1.

However the results show a very weak relationship between measured indoor air temperature and estimated clothing insulation ($R=0.0134$, $p=0.067$), which is in agreement with the observed response from the visual diary. However this result might be due to the analysis design as all participants were grouped in one sample. Further analysis of the data on a participant-by-participant basis is revealed within-subject variations.

Figure 5.35: Monitored results - Regression analysis between monitored (T_a) and (I_{cl}) for all participants with the fitted linear regression lines for each participants.

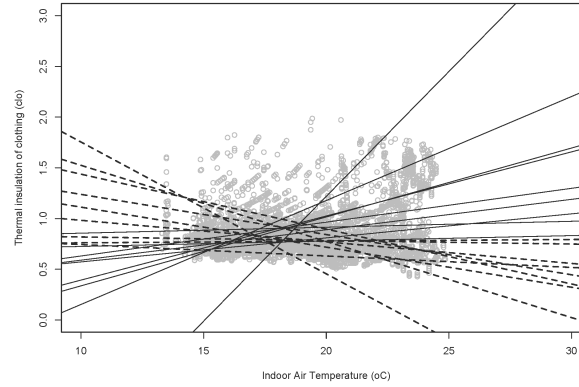


Table 5.3: Summary statistics of the regression analysis between monitored (T_a) and (I_{cl}) for each participant (note: P06 data was missing for the sensor log, and not included in the analysis)

Participants	R	Adjusted R ²	F-statistic	DF	p-value (0.05)
P01	0.31	0.10	154.74	1419	0.000
P02	0.03	0.03	81.25	3108	0.000
P03	0.24	0.05	7.49	125	0.007
P04	0.03	0.00	0.29	258	0.591★
P05	-0.04	0.00	2.27	1159	0.132★
P07	-0.30	0.09	236.84	2462	0.000
P08	-0.16	0.02	5.44	204	0.021
P09	0.37	0.13	76.50	495	0.000
P10	-0.29	0.08	245.51	2651	0.000
P11	0.10	0.01	3.17	312	0.076★
P12	0.39	0.14	11.48	64	0.001
P13	-0.11	0.01	9.72	863	0.002
P14	0.44	0.17	9.34	40	0.004
P15	0.08	0.01	5.01	873	0.025
P16	-0.10	0.01	25.05	2283	0.000
P17	-0.24	0.06	36.69	592	0.000
P18	-0.28	0.08	78.62	956	0.000
P19	0.46	0.21	156.19	585	0.000
P20	-0.33	0.10	13.68	115	0.003

Figure 5.35 shows that one half of the participants slightly increases clothing level as indoor air temperature decreases. However the other half of the participants decrease their clothing level as indoor air temperature decreases. These findings establish that there is a gap between participants self-reported and sensor-observed use of clothing as a response to cold thermal discomfort. While participants reported putting on clothes when they were cold this was not observed for half of the participants. Therefore this suggests that other behaviour-responses may be being employed, such as turning-on/up the heating or localised behaviour responses.

Review of the relationship between air temperature and the most frequently observed response - activity level

Following this analysis, the most frequently observed activity, participants level of motion, was estimated from the output of the SenseCam tri-axis piezoresistive accelerometer as a quantitative, objective, and continuous variable. Its relationship with ambient temperature (T_a) may be evaluated using regression analysis.

Having estimated activity level as a quantitative, objective, and continuous variable in chapter 4, the estimated total acceleration (LA) was then compared to the measured ambient air temperature (T_a) for each participant, see Figure 5.36. The overall sample size amounts to 31,540 data-points, and average of 1,660 per participant. While the results show almost no relationship between activity and indoor temperature, there is a weak negative correlation suggesting that most participants tend to be slightly more active as ambient temperature gets colder. Only 6-participants were less active in colder temperature; this is may be due to the fact that these 6-participants lived in relatively warmer environments and did not experience temperature below 19°C. These findings establish that there is limited support for increased occupant activity at lower temperatures. As participants feel colder, they may chose to adjust their position, their location within the room, or to change room; these form part of the localised behaviour responses.

Figure 5.36: Monitored results - Regression analysis between monitored (T_a) and (TA) for all participants with the fitted linear regression lines for each participants.

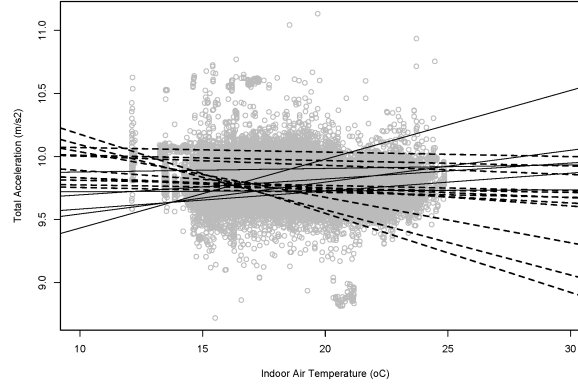


Table 5.4: Summary statistics of the regression analysis between monitored (T_a) and (TA) for each participant (note: P06 data was missing for the sensor log, and not included in the analysis)

Participants	R	Adjusted R ²	F-statistic	DF	p-value (0.05)
P01	0.04	0.00	3.85	2113	0.050★
P02	0.07	0.00	24.99	5759	0.000
P03	-0.05	0.00	2.71	1182	0.100★
P04	-0.17	0.03	13.51	464	0.000
P05	-0.12	0.02	39.60	2509	0.000
P07	-0.04	0.00	4.32	3512	0.038
P08	0.13	0.02	7.58	412	0.006
P09	0.21	0.04	49.15	1044	0.000
P10	0.01	0.00	0.16	3680	0.691★
P11	-0.10	0.01	6.31	676	0.012
P12	-0.14	0.02	22.61	1193	0.000
P13	-0.14	0.02	33.36	1700	0.000
P14	-0.05	0.00	0.46	220	0.496★
P15	-0.44	0.19	489.17	2048	0.000
P16	-0.07	0.01	25.99	4653	0.000
P17	-0.15	0.02	33.16	1350	0.000
P18	-0.22	0.05	99.3	1898	0.000
P19	-0.06	0.00	5.74	1427	0.017
P20	0.18	0.03	11.14	317	0.001

Review of hourly changes in the most frequently reported and observed responses

Using the estimations from chapter 4, mean clothing level was estimated for each hour of the day. As shown in Figure 5.37, there was little variations in clothing levels during the day. This result is similar to the findings by Hunt, D. and Gidman, M. (1982). An increase was observed in the morning from 0.75 clo at 5 am to 0.90 clo at 8 am. Then a slight decrease was observed during midday with 0.81 clo at 12 pm, followed by a slight increase at 3 pm, before falling to 0.61 clo in the late evening (1 am). It should be noted that none of the participants wore the sensors between 2 am and 4 am.

Figure 5.37: Mean clothing levels for all participants throughout the day.

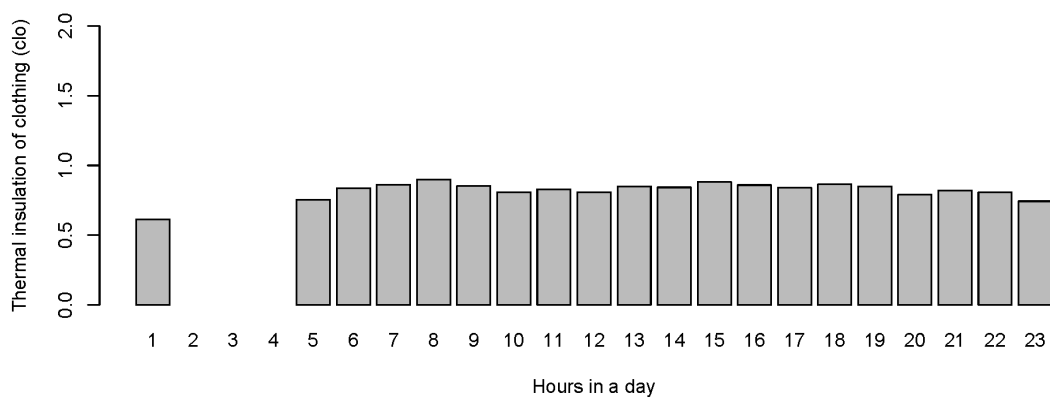
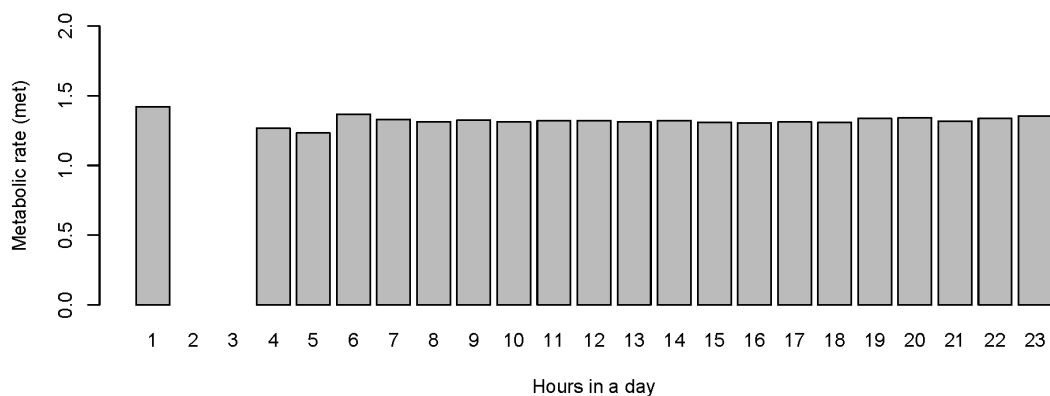


Figure 5.38: Mean activity levels for all participants throughout the day.



A similar analysis was undertaken to review the mean activity level for each hour of the day. As shown in Figure 5.38, there was very little variation in activity levels during the day. This result differs from findings by Hunt, D. and Gidman, M. (1982), which observed a decline in activity from midday. An increase was observed at 6 am with 1.37 met, then a slight decrease with a 'plateau' during mid-day, with 1.32 met at 12pm. Then a slight increase in the evening, reaching 1.34 met at 8 pm.

In summary, these patterns are interesting in reviewing general hourly trends in clothing and activity levels. However the sample size was relatively small, and the results will be influenced by which participant was using the wearable sensor at a specific time, i.e. participants wearing warm clothing may be using the sensors only during the evenings, and therefore the mean clothing level will increase during this period.

5.4.2.3 Observed and predicted information

Indoor temperature and relative humidity

The outdoor weather conditions were used as an indicator of whether the external temperatures were low enough to require space heating. As external temperatures were below 15.5°C for 99.6% of the recording period, CIBSE winter environmental design criteria were taken as benchmarks and compared to indoor monitored conditions (Chartered Institution of Building Services Engineers (CIBSE), 2007).

Monitored indoor temperature and relative humidity are summarised in Figure 5.39, Figure 5.41, Figure 5.42, Figure 5.39 and in Appendix C. Results show that 85% of recorded points fall outside CIBSE benchmark; with 83% of the recorded temperature outside the prescribed range, but 84% of recorded relative humidity within the prescribed range. These results are surprising, as the proportion of recorded time outside the design comfort range was 96% in living rooms and 69% in bedrooms. Overall the mean living room temperature was 18.46 ± 2.69 °C, and the mean bedroom temperature was 18.88 ± 2.67 °C. These are about 0.5 °C lower than the findings by Oseland, N. (1994). With regards to relative humidity, the mean living room relative humidity was 53.91 ± 11.59 %, and the mean bedroom relative humidity was 55.34 ± 12.93 %, which is about 2.1 to 3.5 % lower than the findings by Oseland, N. (1994).

Figure 5.39: Internal monitored temperature and relative humidity in living rooms during the main study, with CIBSE benchmarks highlighted (grey-box).

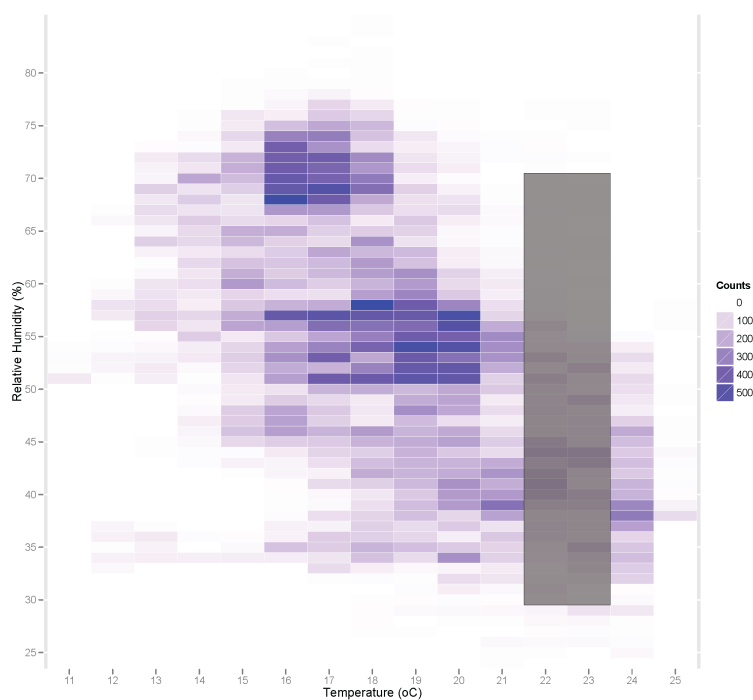


Figure 5.40: Internal monitored temperature and relative humidity in bedrooms during the main study, with CIBSE benchmarks highlighted (grey-box).

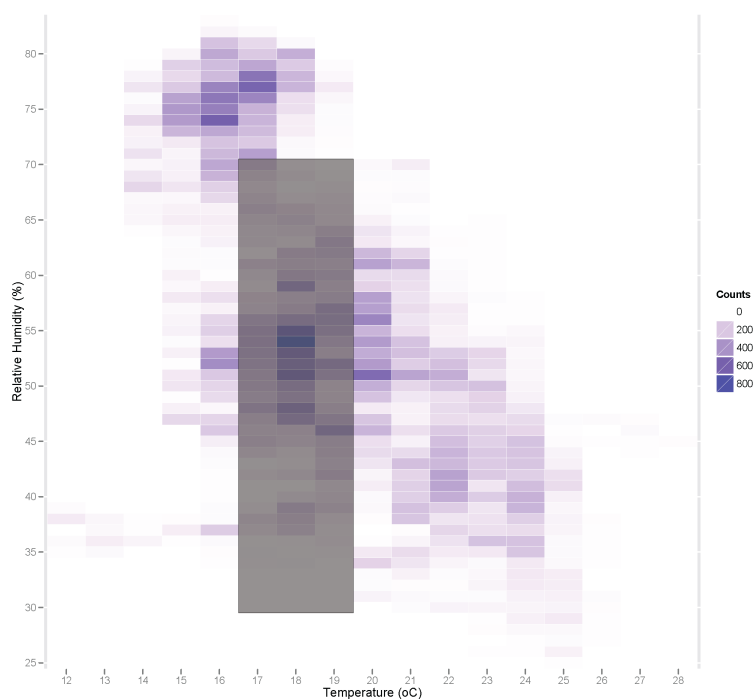


Figure 5.41: Internal monitored temperature in living rooms during the main study, with CIBSE benchmarks highlighted (dotted-line).

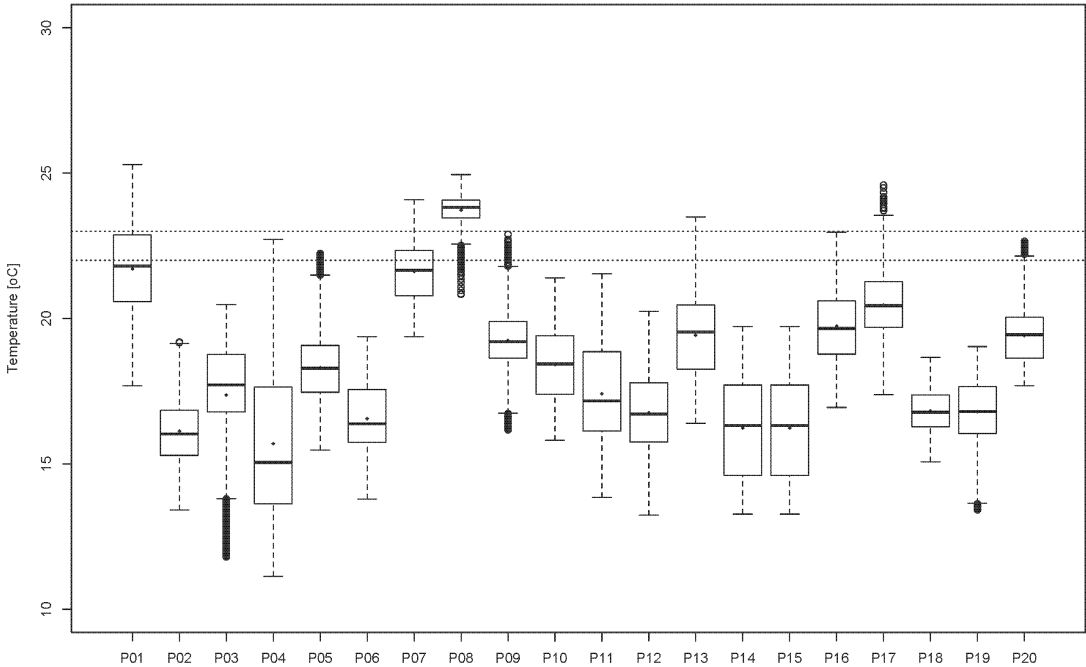
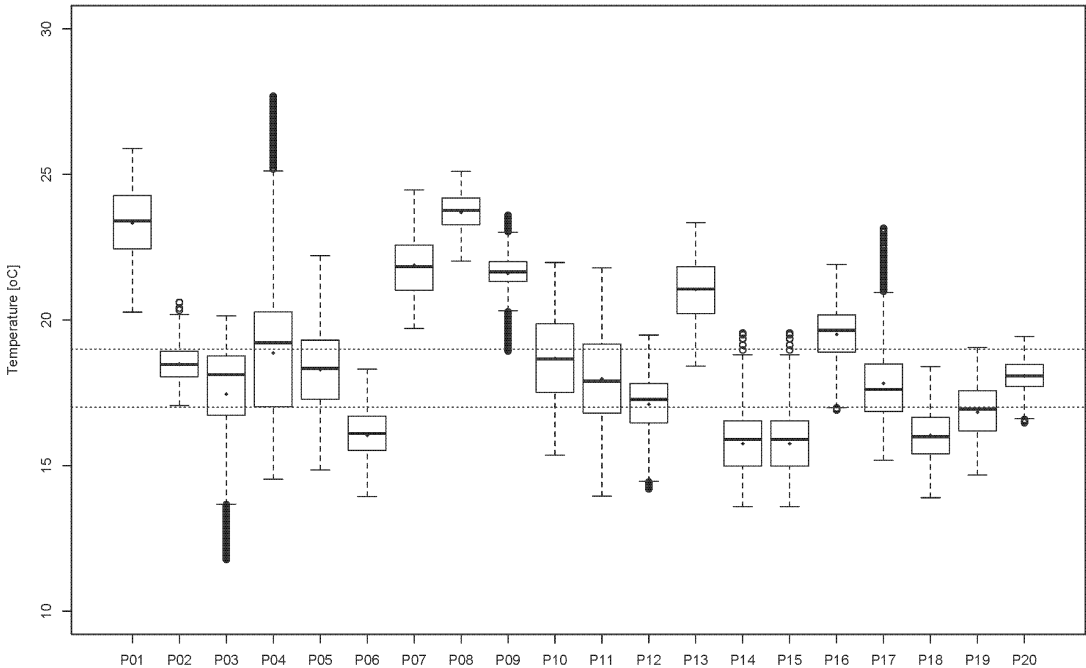


Figure 5.42: Internal monitored temperature in bedrooms during the main study, with CIBSE benchmarks highlighted (dotted-line).



Reviewing the daily temperature profiles for each participant three categories may exist (see Appendix C). There are cases with small variations most likely to be associated with constant heating and thermostatic control; while others show peak-and-troughs most likely to be associated with longer on-off heating cycles. In some cases these appear regular, suggesting programmed timers, in other they are more random and therefore more likely to be associated with manual control. In the first type of dwelling, occupants seem to be using a thermostat as temperatures show minor fluctuations around a mid-value (P02, P08 and P18). In a second, using a timer, regular daily increases in internal temperatures can be observed (P10 and P11). Finally the third type, using manual control, shows more varied temperature profiles throughout the day and from day to day (P04, P09 and P17).

The distribution of internal temperatures also varies; in some homes temperatures in living-rooms and bedrooms are very similar (P03, P05, P07, P08, P10, P11, P16, P18 and P19), whilst in other homes, temperatures in living-rooms and bedrooms differ in levels and profile. These variations may be caused by different zoning practices but also different layouts and orientations.

To follow this analysis, temperature stratification in living rooms and bedrooms were reviewed for a subset of 10-dwellings, see Figure 5.43 and Figure 5.44. This sample excluded all apartments-blocks and only included detached, semi-detached and terraced houses. In living rooms, the amplitude of the mean temperature variation in height may reach 5.3 °C, which is greater than the 3 °C limit prescribed for a category B acceptability by ISO 7730:2005. However in bedrooms, thermal stratification ranges from 0.2 to 1.7 °C, which remains within the benchmarks. In living rooms, half of the sample experienced temperature differences greater than 3 °C for 54% of the time or more. It is also interesting to note that large stratification occurs in relatively cold environments (P01) and warmer ones (P10). One conjecture might be that larger vertical thermal stratification is not only the effect of natural convection but of other factors such as air infiltration through the floor or adjacent surface temperature. As greater thermal stratification was observed in living rooms, further analysis was carried-out to investigate temperature distributions at the 4-monitoring heights. Results show that temperature ranges fluctuate between 0.9 and 7.8 °C and the amplitude of the variations is greater at head height than at feet height. This is an interesting finding and may be explained by a range of factors such as localised heat gains i.e. the occupants or equipment (luminaires, etc.).

Figure 5.43: Air temperature profiles in living rooms, vertical distribution comparison between the 10 cases studied with standard benchmark thresholds (vertical dotted lines).

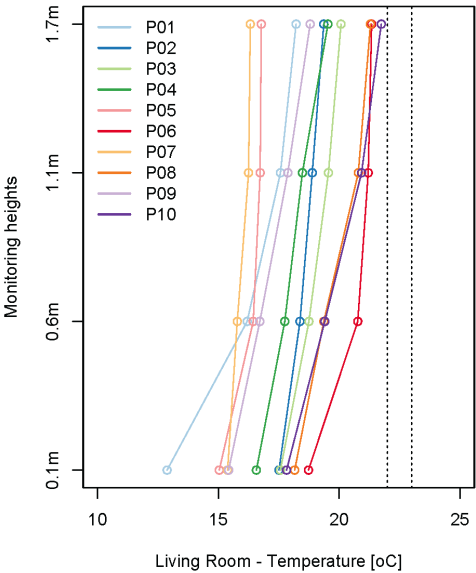
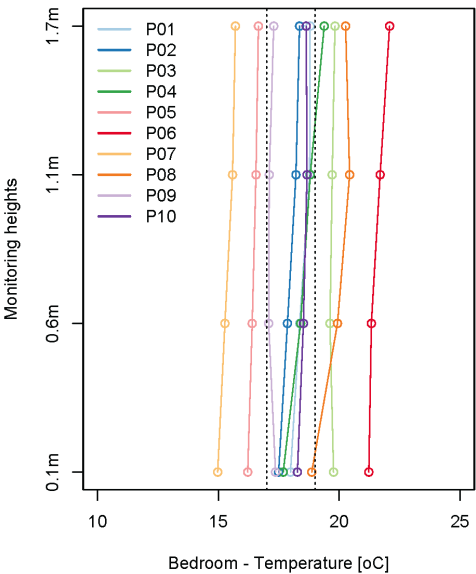


Figure 5.44: Air temperature profiles in bedrooms, vertical distribution comparison between the 10 cases studied with standard benchmark thresholds (vertical dotted lines).



Predicted thermal sensations

As external temperature was below 15.5°C for most of the monitoring period, only the predictive approach may be applied. Participants' predicted thermal sensation was calculated every 5-minutes using ISO 7730:2005, Annex D. The six inputs to the PMV model were as follows:

- Environmental variables: the same estimation methods as the one used for the questionnaires were applied. Air temperature and relative humidity were monitored in living rooms and bedrooms at 0.1m, 0.6m, 1.1m and 1.7m from the ground. Mean radiant temperature was assumed to be equal to air temperature. Relative air velocity was measured during the first visit, and assumed to be equal to 0.1 m/s for the entire monitoring period.
- Personal variables: activity and clothing levels were measured using the methods and results of chapter 4.

The boxplots in Figure 5.45 show the variability of predicted thermal sensation for each participant throughout the monitoring period. This analysis shows that mean PMV for half of the participants is within the bounds of ISO 7730:2005 category B, set at $-0.5 < \text{PMV} < +0.5$. The other half of the sample should be feeling '*slightly cool*' to '*cool*'. The mean PMV for all participants was -0.5 ± 0.7 , which is comparable to the results found by Oseland, N. (1994) with PMV of -0.5 ± 0.6 . As shown in Figure 5.46, 55.3 % of PMV during occupied time was within the bounds of category B. The mean predicted percentage of dissatisfied (PPD) was 19.6 ± 17.5 %, and 56 % of the occurrence were within the bound of category B, set at $\text{PPD} < 10$ %, as shown in Figure 5.47.

Figure 5.45: Predicted mean vote for each participant throughout the monitoring period, with ISO 7730:2005 categories B highlighted as dotted lines.

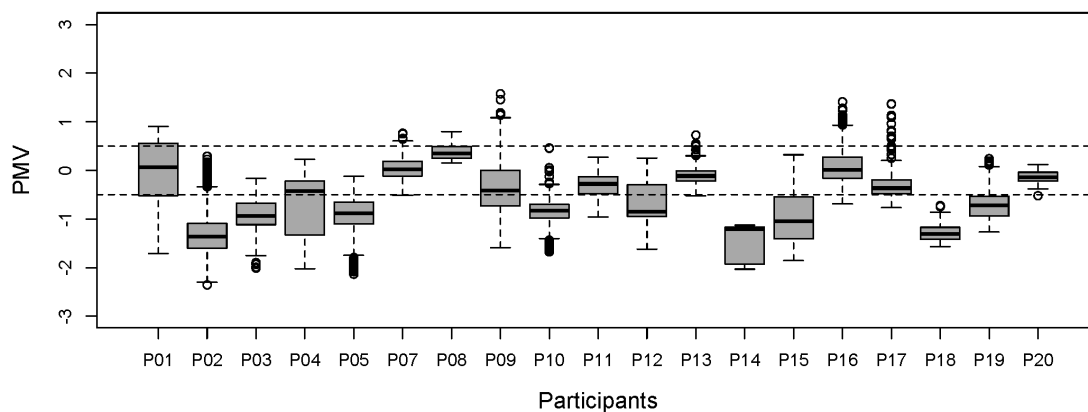


Figure 5.46: Predicted mean vote for all participants throughout the monitoring period, with ISO 7730:2005 categories A, B, and C highlighted as dotted lines and the bound of category B in orange box.

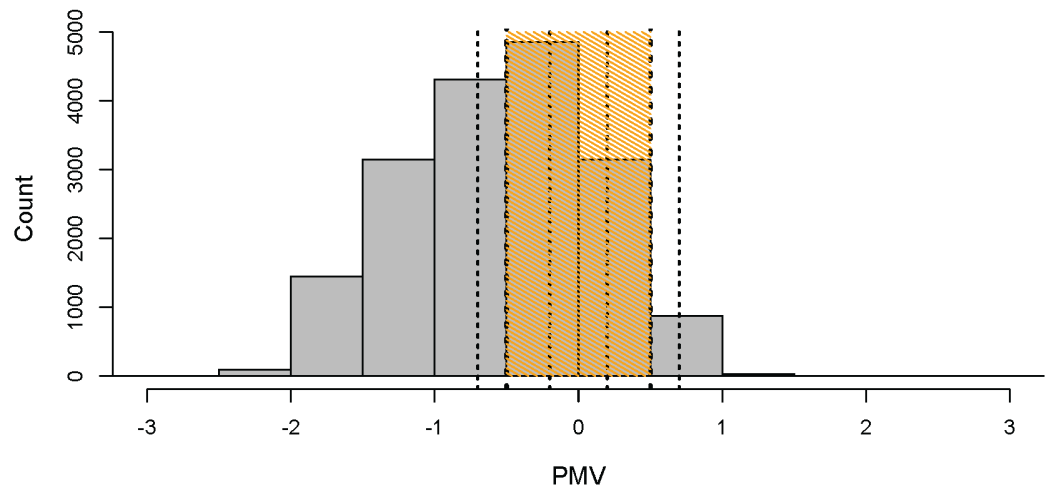
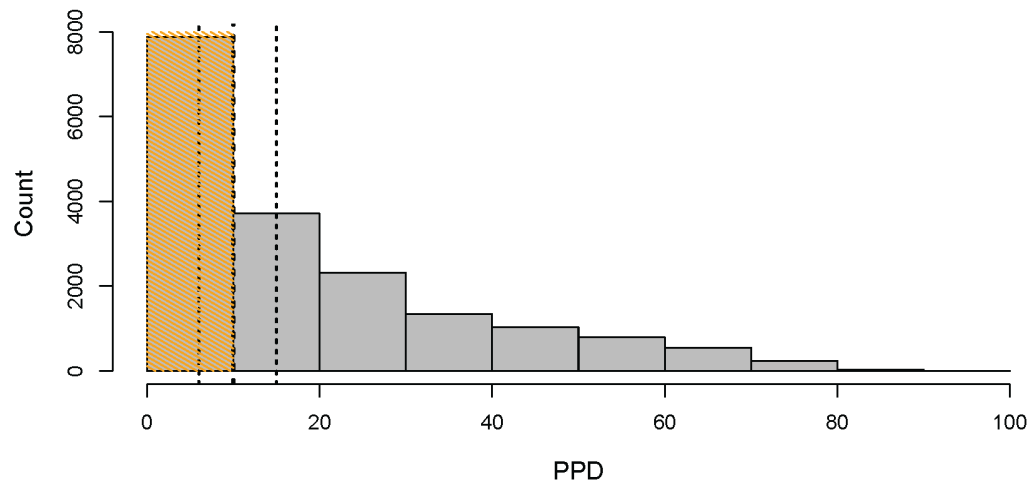


Figure 5.47: Predicted percentage of dissatisfied for all participants throughout the monitoring period, with ISO 7730:2005 categories A, B, and C highlighted as dotted lines and the bound of category B in orange box.



5.4.2.4 Review of the feedback interviews

Along the same line as the pilot study, a feedback interview was carried out during the second visit, and directly after the comfort interview. Most of the comments were similar to the one found in the pilot study, and described as follows:

- *Taking part.* Overall participants were again very interested in the application of wearable sensors. In particular how the SenseCam may used to treat memory loss.
- *The instrument.* Most participants were satisfied with the two wearable devices. Although few participants found the SenesCam's re-setting process confusing and asked for the researcher to come back and explain the process once more. In all cases, the monitoring data were synchronised for the analysis. With regards to the heart-rate monitor, some participants found it to be too tight around their chest; this may have restricted some activities.
- *Failing to wear the devices.* Most participants forgot to wear the SenseCam and heart-rate monitor at least once in the morning or when returning home. A similar analysis process to the pilot study was undertaken to draw a schedule of usage. Pictures from the visual diaries were reviewed for each start time. This confirmed that sometime participants forgot to wear the devices in the morning or when returning home. Moreover the schedule allowed to map-out when both devices were worn concurrently, and when the validation of the activity levels' estimation could be carried out.
- *Privacy.* Most participants did not had privacy concern, as not all pictures were reviewed. For the main study, only the pictures selected by the automated segmentation and the validation processes were reviewed. One participant reviewed the images prior to the second visit, and was satisfied with the content. No picture was deleted. Another participant asked for a copy of the images taken.
- *Hawthorne effect.* Similar to the pilot study, most participants reported feeling less self-conscious of wearing the SenseCam and heart rate monitor after the first hours or first day of use. The first monitoring day was not taken into account in the analysis.
- *Duration.* Most participants felt that 10-days was enough to capture all their different responses to cold thermal discomfort. Only one participant suggested a longer monitoring period, up to four months to cover the entire winter season.

In summary, future studies may consider using different heart-rate monitoring device. Due to very recent developments in sensor technology, new devices use optical heart rate sensors

integrated in wrist-band, such as the Microsoft Band and the Surge from Fitbit. However these devices should be combined with an accelerometer located on the body core (refer to Section 4.3.2). Also as developments in battery and storage technology evolve, wearable sensors may be worn throughout the monitoring period, indoor and outdoor, which will minimise the risk of being forgotten. The monitoring period may also be extended to one month.

5.4.3 Summary of the main study

This detailed case study analysis is based on empirical data. It includes the collection of information from questionnaires, semi-structured interviews, diaries, physical surveys, and environmental monitoring. Results provided insights to identifying the responses of most importance to thermal discomfort in dwellings; the most frequently reported response being *change in clothing level*, and the most frequently observed response being *change in activity level*. Further analysis has reviewed the relationship between indoor air temperature and clothing levels. Results show that one half of the participants increased their clothing levels as temperature decreased, and the other half of the participants decreased their clothing level. This result is interesting as most participants reported putting on items of clothing when feeling cold. In summary this result confirms a gap between what people say and what people do. Moreover people may be engaging in other behaviours to stay warm, including variations in activity level as observed in the visual diary.

This study has also highlighted the importance of referring to standard benchmarks and comparing results to these. Interestingly, monitored indoor environmental conditions were outside the prescribed thresholds for most of the occupied time. This raised questions in the assumptions made in the formulation of those standards. Moreover when environmental conditions were below the standard guidelines, occupants may have been engaging with adaptive behaviours not accounted for in the standards model.

5.5 Summary

This chapter aimed develop and apply a methodological framework to monitor occupants cold thermal discomfort responses. To this effect field studies were carried out during the winters of 2010, 2011 and 2012. These involved a mixed-method framework, including occupant and building surveys. The data collection process was in two stages .

First a pilot study was carried out to assess the data collection methods. It consisted of the following 7-parts:

- Recruitment of participants with a sample frame based on dwelling and socio-demographic characteristics.

- Calibration of monitoring equipment.
- Visit to each individual dwelling, during which a socio-demographic questionnaire, a thermal comfort questionnaire and building surveys were carried out. In addition the monitoring instruments were introduced to the participants and installed.
- Monitoring period of three days, collecting environmental and personal information.
- Second visit, during which a feedback interview was carried out, and monitoring equipment collected.
- Implementation of a focus group.
- Review of the information collected, data processing and analysis.

After reviewing the results of the pilot study, the main field study was carried out during the winters of 2011 and 2012. It consisted of the following 6-parts:

- Recruitment of participants with a sample frame based on physiological characteristics.
- Calibration of monitoring equipment.
- Visit to each individual dwelling, during which a socio-demographic questionnaire, a thermal comfort questionnaire and a building survey were carried out. In addition the monitoring instrument were introduced to the participant and installed.
- Monitoring period of ten days, collecting environmental and personal information.
- Second visit, during which a semi-structured interview was completed, and monitoring equipment collected.
- Review of the information collected, data processing and analysis.

This chapter answered the research objectives set out in the research design, by (1) reviewing and evaluating existing and novel methods to investigate people's cold thermal discomfort responses, (2) identifying a set of case studies and completed empirical studies, (3) developing an analysis method to identify and quantify occupants responses. Drawing on from these results, the following chapter will be discussing these findings.

Chapter 6

Discussion

6.1 Outline

As described by DECC (2012b), reducing domestic energy demand may be achieved through energy conservation or energy efficiency measures. With regard to the practices used to keep warm at home, it is assumed that people are only influenced by two factors, (1) energy cost, and (2) indoor temperature level through the use of heating controls DECC (2012b). These assumptions undermine the multiple reasons why people manage their own thermal comfort, and the multiple ways they achieve winter warmth. With this in mind, this research investigates how people respond to thermal discomfort in winter, with the aim to develop a method to monitor these responses, and uncover their variations. Variations may be in the type of responses employed, but also in their frequency and duration.

As reviewed in Chapter 2, thermal comfort has been the focus of a number of empirical studies in controlled and free-living environments; however there is still a lack of evidence on what people do to achieve winter comfort. Current standard methods use observation and/or surveys to assess predicted and actual mean vote; the results only focus on how people feel, and not on what they do. Other standard methods aim to estimate indoor operative temperature, again the results are used to assess "*compliance*" to regulations rather than exploring what people do. One reason for this oversight might relate to the assumption that people will act if uncomfortable by changing the operative temperature, their clothing or activity level. Recent sociological and ethnographic studies have used interviews to gain insights on people's responses to cold; however these are reported accounts from participants, which may differ from actual behaviours and practices. Considering the current methodological frameworks, this research proposes a new mixed-method approach to monitor people's responses to cold thermal discomfort using ubiquitous sensing technologies. In particular the mixed-method approach provides an alternative method for determining actual behaviours and their variations in type,

frequency and duration. Furthermore the method allows for continuous monitoring over time, addressing dynamic change of conditions.

To follow the results and analysis in Chapter 4 and 5, the mixed-method approach will be critically reviewed in this Chapter; in particular the internal and external validity. Finally this discussion will lead to a the development of a framework to monitor thermal discomfort responses variability.

6.2 Internal validity

6.2.1 Study design

As reviewed in Section 5.2.1, only one comfort survey was undertaken with each participant using a 7-point Bedford Scale (ISO 10551:2001). This allowed to complete a standard assessment of thermal comfort by comparing predicted (PMV) and actual mean vote (AMV). However during the monitoring study the participants were not asked to rate their thermal sensations. The main reason was that if participants were to assess and reflect upon their level of comfort repeatedly, they might have change their behaviours. This may have in turn introduce bias in the study. The research was focusing on monitoring behavioural response to cold thermal discomfort, it differs in its aims from other studies focused on monitoring occupants thermal comfort level. As the monitoring study did not include repeated comfort surveys, the observed behaviours may not have been responses to thermal discomfort but responses to physiological or social factors, as reviewed in Section 5.4.2.2. For example, a participant might have move to a different room in the house to complete a task, not to increase activity level, or chose a warmer location. To address this bias, the frequency of observed behaviours may be reviewed against internal temperature level. The assumption is that if the home gets colder, the frequency of a specific behaviour may increase. Future studies may gather individual participant's reported responses using interview. Then similar filtering algorithm as the one developed in this research may be used to estimate the frequency of each of these responses for different internal temperature levels. This would allow to uncover which behaviour is more recurrent when the home is colder.

6.2.2 Data collection

As the research employs a range of sensors to collect information, each device may introduce measurement errors. To address this bias, it is import to review the accuracy and to test the precision of each sensor. As described in Chapter 4 and 5, the study used four devices, two environmental instruments (HOBO U12-012 and Testo 425 anemometer) and two wearable instruments (SenseCam and Kalenji heart rate monitor). Calibration tests were undertaken, most

of them in climate chamber. Some of the results were compared to standard benchmarks (ISO 7726:2001), however there is currently no standard requirement for the accuracy and precision of heart rate monitor or accelerometer.

Further bias might have been introduced by the positioning of sensors. As reviewed in Section 5.4.2.3, vertical thermal stratification may reach 5.3°C in participants' homes. Therefore the height at which the environmental sensors are positioned may have a great influence on the monitored results. Moreover there might be further variations in the horizontal plane. This may be caused by local heat sources such as a fridge or a television, or by solar radiation. Thus the output of the environmental monitoring is based on '*spot*' measurement, rather than a representative measure for the whole house. Consequently future studies may deploy a greater number of environmental sensors to monitor hygrothermal conditions in all rooms in the house. Combined with indoor location sensing, the estimate of thermal insulation of clothing may be more precise.

To follow on from the conclusions of Section 5.2.7, future studies may apply indoor location monitoring by using a combination of sensors, including accelerometer, magnetometer, gyroscope and altimeter. The output from the altimeter or atmospheric pressure sensor may also be used in the estimation of metabolic rate. As described in Section 4.3.2.3, the methods used in this research do not take into account the energy required to sit, or to climb/descend stairs. The estimation of vertical movement will then increase the precision of the estimation of activity levels.

6.2.3 Data processing

As described in section 4.3.2.2, the estimation of activity level using heart rate applied standard equations from ISO 8996:2004. As this estimation method has an accuracy of $\pm 10\%$, calibration tests in climate chamber were undertaken. The results were conclusive, and found that low level of metabolic rate varied from 74.5 to 90.8 W/m² or 1.3 to 1.6 met. To complement this experiment, validation checks using the visual diary were carried out, as described in Section 4.3.2.2. Data log with resting to very high metabolic rate were randomly selected, then the associated pictures were reviewed. The results showed that the estimation method did assigned adequate value of metabolic rate. However other sequence may differ as variations in heart rate may be caused by variations in activity level but also by other factors such as emotions. This will introduce bias in the estimation of metabolic rate. To address this limitation, cross validation may be carried out using another method of estimation. This research undertook concurrent monitoring of activity level using accelerometry. Here the analysis method applied equations from literature (Ralston, H., 1958), which use SI units rather than "*activity counts*". The in-

dependent variables are the participants' speed and body surface area. This analysis method does not take into account variations in participants' gender or age, which may introduce bias. Similar validation checks using the five activity classifications were undertaken. The results were also conclusive as each classification was estimated within the ranges of ISO 8996:2004. Further studies may estimate the precise accuracy of this estimation method.

With regards to the estimation of clothing level, the analysis method in this research applied a standard equation from ASHRAE 55:2013. Unfortunately there is little documentation about the origin of this equation only in the book by Fanger, P. (1970), which describe theoretical principles of heat transfer and the results of a series of climate chamber experiments. Moreover this equation can only be applied when the air velocity is equal to, or lower than 0.1 m/s, and the participants are sedentary. This is due to the fact that higher air movement will alter the ratio of convective and radiative flows, thus altering operative temperature. Also, it will alter the heat transfer coefficient between the clothed surface of the participants and the room (CIBSE, 2006). The filtering algorithm applied in this research selected the data entries of the sensors' log when participants were sedentary. However, the room air velocity was only measured once, at the start of the study. Although the study was undertaken during the winter season, participants may have opened windows, which would have increased the air movement. Future studies may monitor air flow in each room, or install sensors on windows and doors.

The sequencing of the data analysis process started with the review of the semi-structured interviews. Content analysis was applied to the interview-transcripts to reveal participants' reported responses to cold thermal discomfort. In Section 5.4.2.2, six categories of responses were identified, including (1) interacting with the heating system, (2) putting on garment(s), (3) having warm drinks or food, (4) changing body position, location or room, (5) closing windows or curtains, and (6) using a hot water bottle or having a warm bath. Using these six categories of responses, the output of the sensors were analysed and filtering algorithms developed to automatically detected these responses within the sensors' logs. Although this mixed-method approach enabled automated segmentation processes to be developed, only the responses referred to by the participants were reviewed. This might introduce bias, as other participants may have different responses.

The visual diary was used extensively to develop the filtering algorithms, and to validate the estimation of activity and clothing levels. To comply with the conditions set-out by the ethical approval, only the researcher and the two supervisors were permitted to review the pictures and only the researcher did so. Therefore systematic errors may have been introduced by the main coder. In particular, the SenseCam's camera has only a 119 wide-angle lens, thus it may

be difficult to see if a participant was wearing a hat. In future studies, multiple coders should review the pictures; a similar protocol to the one described in Byrne, D. et al. (2010) may be followed.

Finally further bias may be introduced by the "*observer effect*". To follow the results of the feedback interviews, the first monitoring day was not taken into account in the analysis. Although most participants reported feeling less self-conscious of wearing the SenseCam and heart rate monitor after the first few hours, the potential Hawthorne effect may continue throughout the monitoring study. Future studies may look at developing a similar device than the SenseCam but without the in-built camera.

6.2.4 Results

As described in Section 5.4.2.3, 83% of recorded temperatures for the overall sample were outside the prescribed benchmarks (CIBSE, 2006). Reviewing the temperature distributions for each participant, most homes experienced temporal variations of 3-5 °C for 95% of the monitoring time (See Figure 5.41). These low indoor temperature levels may not only be influenced by the occupants' behaviours but also by the building heating systems, the building fabric (thermal insulation and airtightness), the built form and orientation. Furthermore the amount of time each participant spent at home will have a significant effect on the indoor temperature levels. Therefore the environmental monitoring results should be assessed in the context of the built environment and socio-economic factors.

Both the pilot study and main study monitored two set of participants living in the same dwelling; P07 and P11 for the pilot and P14 and P15 for the main study (refer to Section 3.2.2). Results show little difference in the type and frequency of responses within both groups. However with regards to the main study, P14 and P15 seemed to use different parts of their home. P14 tend to spend most of the time in the kitchen, while P15 was mainly in the first floor office. Further studies may explore the notion of "*negotiated comfort*" between participants, using similar methods described in Tweed, C., et al. (2014). Furthermore the results of the focus group, revealed that "*friends and family*" are reported to be the most influencing factor when responding to cold thermal discomfort. In particular, the control of the heating system may be the "*responsibility*" of a dedicated resident. Future study may explore these relationships within the home.

During the first visit comfort surveys were completed with each participant. The results, summarised in Sections 5.3.2.1 and 5.4.2.1, show that most participants reported to be "*slightly warm*", "*warm*", and "*hot*", and were "*comfortable*". This is an interesting result, as warmth was considered a comfortable state, contrary to being cold which was deem "*uncomfortable*".

This add to the debate on thermal neutrality (Brager, G. et al., 1993), as being comfortable may not only be thermally neutral but also being warm.

"Warm drinks and food" was reported to be the third most frequent response to cold thermal discomfort in both the focus group and the semi-structured interviews. However *"warm drinks and food"* may not add significant amount of heat to the local environment around the participants. Therefore the effect of this response may be from two means; first the physiological effect of digestion, and second the psychological effect of alliesthesia (de Dear, R., 2011). Moreover participants may not have *"warm drinks and food"* as a response to feeling cold but to fulfil their physiological need of eating and drinking. Future studies may investigate the frequency of *"warm drinks and food"* intake over longer periods of time, using a SenseCam or food-diary. Results will not revealed the reason for eating (i.e. hunger, habit or thermal comfort), but it will show the variations in frequency as temperature increase or decrease. Thus, the diary may be complemented by questionnaires or interviews.

Following on from this last comment, little change was observed in clothing and activity levels during the course of one day (Section 5.4.2.2). However variations may be more important from day to day, over the course of one week or one month (Morgan, C. and de Dear, R., 2003). Future studies may be carried out over longer period of time to investigate these potential variations.

6.3 External validity

In this research, two empirical studies were undertaken, first a pilot study with 11-participants, then a main study with 20-participants. Although the number of observations was very large, about 37,000 images in the pilot and 180,000 images in the main study, the sample size of participants was relatively small. Therefore findings are not representative, but capture some of the variability in people's response to cold thermal discomfort. Furthermore the two studies allowed for a mixed-method framework to be developed including data collection and analysis methods. Future studies may apply a similar framework on a larger sample size. For example, the different technologies focusing on energy efficiency may be tested in a randomised controlled trial.

As reviewed in the study design, the participants taking part in the main study were related to the University, and therefore they may have similar attitudes and lifestyles. This may have introduced bias in the results. Also having volunteers to take part in the study, the participants would have been interested in winter comfort, and how their home *"performed"*, as highlighted in the feedback interviews. Therefore, the participants taking part in this research may been

able to reflect on cold adaptation more than most because of their interest in the topic. Future studies may look at recruiting participants from an established subject pool.

The research was set in people's home. This environment may allow for greater adaptive opportunities than non-domestic buildings. If a study was to be carried out in office setting, then a similar framework may be applied. The set of wearable sensors may not include a camera for privacy concerns, yet additional factors may be monitored; for example operational power of computer or lighting may enable participants' location to be ascertained.

The study focussed on winter adaptation, yet a similar framework may be applied to summer adaptation. The set of sensors may need to be revised. In particular, air velocity was measured during the first visit and found to be below 0.1 m/s in all dwellings. This concurred with the assumption that indoor air velocity would be around 0.1 m/s during winter as little window and door operation occurs (Hong, S. et al., 2009). However during the summer, windows and doors may be opened more frequently. These opening behaviours will need to be monitored, as this may affect air flow in the dwelling as well as the operative temperature and the heat transfer coefficient between the clothed surface of the participants and the room. In addition to the filtering algorithms should be revised to focus on responses to warmth.

Finally, the dwellings were all located in the South East of England, therefore participants may apply similar local adaptation responses. Other studies may be carried out in different regions or climates where responses may be influenced by specific geographical and cultural features. The framework developed in this study may then be used to investigate variations in local adaptation.

6.4 Framework to monitor thermal discomfort responses

This thesis aimed to develop a framework to monitor the variability in cold thermal discomfort responses. The thesis's research question relates to the identification and the variability of behaviour responses. Using content analysis of interviews, and automated segmentation of visual diary data from wearable sensors, occupant self-reported and observed responses to thermal discomfort were compared. Results show a marked difference between them. Most participants reported that if feeling cold, they would put on an item of clothing. In contrast, observed responses identified through the observation of the automated visual diary are very different, as participants increased clothing only in 1.4% of the observations made. This observed result is confirmed by a relatively weak relationship between measured air temperature (T_a) and estimated clothing insulation (I_{cl}). The latter parameter was estimated from measured temperature at the surface of the clothing on participants chests (T_{clo}) and measured air temperature (T_a), us-

ing ISO 7730:2005. These findings establish that there is a gap between reported and observed responses in the use of clothing as a response to cold thermal discomfort. The absence in observed increases in clothing insulation levels may indicate that other behaviour-responses may be employed, including adjusting the heating, or localised behavioural responses. The probability of these responses may be dependent upon personal or environmental characteristics, including the person's age, room thermal stratification amplitude, or heating system controls.

From this study one might consider the heat flow around the body as a simple one-dimensional system; where the temperature at the surface of the clothing is a function of skin temperature (T_{sk}), ambient temperature (T_a), temperature derived from localised behaviour (T_{bev}) and the resistances in-between. The reduction of the inputs and associated resistances to a single node may be represented as an application of the Millman's Theorem, where:

$$T_{clo} = \frac{\frac{T_{sk}}{R_1} + \frac{T_a}{R_2} + \frac{T_{bev}}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \quad (6.1)$$

Findings from this study suggest that all three resistances in the model, including R_1 , the resistance of clothing, remain largely constant. This leaves variation of T_a (through controlling heating systems) and variation of T_{bev} (through a range of local behavioural responses) as the observed mechanisms for cold thermal discomfort alleviation.

The review by Brager, G. and de Dear, R. (1998) identified these localised behaviours as part of behaviour adaptation, made consciously or unconsciously by the occupants. These may be personal, technological or cultural adaptive actions and practices, and are influenced by climate, socio-economic constraints and physical context, including the level of control a person has over the surrounding environment. In the current standard predictive model, the 6-inputs will be affected by behavioural adaptation. For example, R_1 - clothing insulation (I_{cl}), might increase if one puts on a jumper, whilst ambient air temperature (T_a), might decrease when changing room. However the localised actions (T_{bev}) are not accounted for, as these might not have a physiological or physical effect but a psychological effect. The study by Baker, N. and Standeven, M. (1994) aimed to identify these adaptive processes and to incorporate the findings into a predictive comfort model. However the results from observations and questionnaires only gathered information on the subjectively reported use of clothing and activity. This calls the reliability of the methods deployed in Baker's study into question, particularly in light of the findings of this thesis. In contrast the methods developed in this research allow the capture of a much wider range of adaptive behaviours. Perhaps as significantly, it also allows these behaviours to be quantified. In practice, further studies could explore different practical scenarios, including the following:

- Localised action if all input variables stay constant but T_a decreases, one response could be to *have a warm drink* then T_{bev} increases and T_{clo} increases as a proportion of T_{bev} and R_3 .
- Heating if all input variables stay constant but T_a decreases, one response could be to *put the heating on* then T_a increases and T_{clo} increases as a proportion of T_a and R_2 .
- Changing room if all input variables stay constant but T_a decreases, one response could be to *move to a warmer room* then T_a increases and T_{clo} increases as a proportion of T_a and R_2 .

In summary, this study approach allows for the creation of a three-tiered framework, mapping behaviour-responses to cold sensations, consisting of (1) increasing clothing insulation level, (2) increasing operative temperature by adjusting the heating system, and (3) increasing the frequency, duration and/or amplitude of localised behaviour responses, including for example warm food or drink intake, changing position, changing location within the same room or changing change room. This framework may in the future be incorporated into an adaptive predictive approach (Yao, R., Li, B. and Liu, J., 2009) or as part of a feedback loop where the previous state of thermal comfort may be revised by current adaptive behaviour to form future state of thermal comfort.

In summary, occupant self-reported and observed responses to thermal discomfort are compared and contrasted, with results showing a marked difference between them. This led to the development of a new framework including localised behaviour responses.

6.5 Summary

This chapter reviewed the internal and external validity of the research, then a new framework was introduced which combined the studies' outcomes. In summary, this research demonstrates how integrating qualitative and quantitative methods provides new insights into winter thermal comfort adaptation at home. In this instance, semi-structured interviews revealed participants reported responses, which were used to develop filtering algorithms to analyse monitoring data. The results illustrate the diversity of ways to live with winter cold.

The research showed the importance of localised behaviour adaptation. For instance, participants took advantage of the spacial diversity in thermal conditions by changing location within a room or changing room. This may be identified as a form of thermal comfort zoning. Also participants used specific items such as blanket or hot water bottle. These localised behaviours may allow for homes to be heated to a lower set point, introducing a "base-load"

complemented by local adaptation. With regards to policy implications, systems such as heat-pump and district heating would suit this constant energy demand, and "*lower-grade*" heat demand. This may help in the quest to reduce peak energy demand at different times of the day and over the heating season. However, as reviewed in Chapter 2, thermal comfort practices may be part of a "*way-of-life*". One may chose to be frugal with his/her home heating for environmental reason, while others may be self-indulgent (Hinton, E., 2010). Moreover different occupants will have different perceived norms of thermal comfort. Therefore future studies may aim to categorise heat practices. One challenging area of future research would be to explore the heat practices of a "*group*" of individuals in dynamic thermal environments. The participants may have similar or varied thermal norms and cultural narratives. For example, each member of a family may be monitored using the methods applied in this research. The data gathered may then be used in an empirically grounded agent-based model to test scenarios of negotiated comfort practices.

Chapter 7

Conclusion

7.1 Summary of findings

The need to identify occupants behaviour-responses to thermal discomfort during the heating season has become a priority in the quest to reduce energy demand. The current models have long been associated with people's behaviour, by predicting their state of thermal comfort or discomfort. These assume that occupants would act upon their level of discomfort through two types of responses: involuntary mechanisms of thermoregulation, and behavioural responses. This research seeks to investigate the variability of reported and observed behavioural responses in residential buildings during the heating season.

The current models used to assess human thermal comfort are of two types: adaptive and predictive models. Adaptive models are derived from empirical studies, and assume that occupants preferred indoor operative temperature varies with external air temperature, and that this relationship is linear. The second type of thermal comfort models are based on physical and physiological principles, and have six input variables: ambient air temperature (T_a), mean radiant temperature (T_r), water vapour partial pressure (Pa), relative air velocity (v_a), metabolic rate (M) and thermal insulation of clothing (I_{cl}).

Although much research has focused on developing models to assess thermal comfort, less is understood about the nature and strength of the relationships between the models' variables. This research reviews the current standard models and reports on an evaluation of global sensitivity of the models as described in standards and guidelines. This sensitivity analysis provides an insight into how the model dependent variables respond to changes in the independent variables. Further analysis assesses which inputs have the most and the least influence on the dependent variables. As described in the literature review, the adaptive models only independent variable is external air temperature, which implies that this environmental variable is the main influencing factor in determining occupants level of thermal discomfort. On the

other hand, the predictive models appear to be most sensitive to personal variables: metabolic rate (M) and thermal insulation of clothing (I_{cl}). In field studies these personal variables are often estimated with a great degree of error. In building simulation studies these variables are given constant values as a function of the seasons and the building or room types. Considering that personal variables are the most influential variables, this high level of inaccuracy will undoubtedly reduce both accuracy and precision of the results of the models.

To address these two issues, this research introduces a mixed-method framework drawn from psychological and physiological studies. Environmental monitoring and automated visual diaries with wearable sensors (including tri-axis accelerometers, heart-rate monitors and temperature sensors), provide measured input from which metabolic rate and thermal insulation of clothing were ascertained over continuous period of time. This mixed-method was applied to twenty dwellings over a period of ten consecutive days, in the South-East of England during the winters of 2012 and 2013.

Results from this experimental investigation generated probability distributions from the levels of metabolic rate (M) and thermal insulation of clothing (I_{cl}) in a residential setting during the winter season. Surprisingly, the mean (I_{cl}) level was 0.82 clo, which is lower than the 1 clo prescribed by EN 15251:2007. On the other hand measured mean (M) was 1.32 met, which is higher than the 1.2 met also prescribed by EN 15251:2007. In summary the standard (M) and (I_{cl}) values differ from the measured values, although both are within the standard deviation of the mean as 1 clo is within 0.82 0.2 clo and 1.2 met is within 1.32 0.13 met.

As (M) and (I_{cl}) are the most influential input variables in predictive models, these observed differences from the standard values may have great impact on the output. Using the empirical study monitoring results as inputs, different scenarios were tested. A reduction in (I_{cl}) from 1 to 0.82 clo reduces the mean Predictive Mean Vote (PMV) from -0.23 to -0.51; which is then outside the bound of category B acceptability of ISO 7730:2005. In parallel, an increase in (M) from 1.2 to 1.32 met increases the mean PMV from -0.87 to -0.57; which is still outside the bound of category B but inside the bound of category C of ISO 7730:2005.

This research introduces a mixed-method framework to estimate (M) and (I_{cl}) as objective, quantitative and continuous variables. Beyond reviewing the standard thresholds, this method may be used in larger studies to generate probability distributions, which may be used as input to building energy simulation (BES) programs, building in greater thermal variability and making simulated thermal comfort analysis more robust. Moreover, the (I_{cl}) value in this study was 0.18 clo lower than the assumed typical value. This low clothing level may partially be compensated by higher observed metabolic rate. When combining these results with environmental

monitoring, the predicted mean votes were substantially below those expected in the standard model, with observed values of -0.54 0.65 PMV score. This suggests that occupants may have been engaging in other adaptive behaviours, not currently accounted for within the standard models.

The second part of the research focuses on identifying these adaptive behaviours. One of the key research challenges is the gathering of accurate measurements, while using discreet observatory methods to have minimum impact on peoples behaviour (Hawthorne effect). Drawing methods from thermal comfort research and psychology, a pilot study was carried out in the South-East of England during the winter of 2011. Ten dwellings were each monitored over a period of three consecutive days, two weekdays and one weekend day. One of the tools used, the SenseCam, facilitated an automated diary collection by logging occupants responses systematically. Of similar size to a badge, this recording device takes photographs when triggered manually and automatically by timer, or by changes in sensors readings. It incorporates a temperature sensor, a light intensity sensor, a passive infrared detector, a tri-axis accelerometer and a magnetometer. This device provided a visual diary of participants whereabouts in their home and a record of measurements taken by each sensor (excluding audio recordings).

The recording period ran through three consecutive days, which generated around 3,200 images for each participant. This six-week study was followed by a focus group, which was attended by nine of the eleven participants. Using content analysis, the focus group's transcripts revealed that the most likely responses to thermal discomfort for the sample group were: (1) interacting with the heating system via TRVs, room thermostat or programmers (44%), (2) putting on an item of clothing (38%), and (3) food or drink intake (12%). Although this focus group revealed an understanding of what people believe they do when feeling cold at home, methodologically the results may be influenced by 'group-effects' - where participants opinions may be prone to culturally expected views rather than individual ones - and 'moderator-effects' - where participants feel the need to please the moderator.

To follow this review, the visual diaries obtained were analysed using a manual segmentation approach. Each image was labelled using six criteria, including: (1) image number, (2) when and (3) where the image was taken, (4) how many persons where in the room, (5) clothing and (6) activity levels. All images were visually inspected by playing them sequentially, in relation to each participant. Adjacent images were compared. If a change in one of the six criteria occurred, a new event was identified. Results show that the most frequently observed response was participants changing location. Although providing interesting insights, this segmentation approach is time-consuming and introduces bias in the observation.

In summary the pilot study enabled the evaluation of data collection and analysis methods. A larger main study was carried out in the South-East of England during the winters of 2012 and 2013, incorporating lessons learnt from the pilot study. Twenty dwellings were each monitored over a period of ten consecutive days using a similar mixed-method approach. Initially, two questionnaires were completed with the householders, one focusing on socio-demographic variables, and the other on thermal comfort ratings. In addition, a building survey was carried out both internally and externally, using an RdSAP worksheet. Data collected includes construction type and details of the heating system. Following this assessment, monitoring was carried out using automated visual diary, wearable sensors and environmental sensors. Finally, interviews were conducted at the end of the ten monitoring days. Using content analysis and automated segmentation, results show a marked difference between occupant self-reported and observed diary responses to thermal discomfort. Adjusting clothing level was most the frequently reported response, while adjusting activity level was the most frequently observed response. This establishes that there is a gap between what participants say they do and their observed behaviour toward cold thermal discomfort.

Drawing on these results, a three-tiered framework mapping behaviour-responses to cold sensations was developed. It consisted of (1) increasing clothing insulation level (I_{cl}), (2) increasing operative temperature by turning the heating system on/up (T_a), and (3) increasing the frequency, duration and/or amplitude of localised behaviour responses (T_{bev}).

7.2 Key findings and practical implications

This research gathered different types of data, which may be summarised as follows:

- Subjective and qualitative data from the focus group and the interviews;
- Subjective and quantitative data from the questionnaires;
- Objective and qualitative data from the visual diaries;
- Objective and quantitative data from the building surveys (e.g. dwellings' age band) and the various monitoring sensors.

This diverse type of data requires different analysis methods, ranging from content analysis, to descriptive and inferential statistics. The most challenging was the analysis of the visual diaries, which called upon automated segmentation methods. Categories of behaviours were first determined using the results of the subjective and qualitative data analysis. Then, filtering algorithms were written to identify these behaviours within the wearable sensors output,

and validated using images from the visual diaries. For example one participant may chose to change room when feeling cold. This change in location will produce a change in accelerometer readings' levels and duration, which may be confirmed or not the visual diaries' images. In summary, to identify thermal discomfort responses variability, a mixed type of data were gathered and a mixed type of analysis techniques were used. Likewise the results are of two types, quantitative (e.g. indoor temperatures and PMV levels) and qualitative (e.g. reported and observed behaviours). Although a very large number of observations were carried out, the study's sample size was relatively small due to the exploratory nature of this research. Therefore the quantitative results are not representative, and only illustrate the outcome of this study. The strength of this research relies in the development of a novel monitoring techniques to identify the variability of thermal discomfort responses.

As reviewed in the Introduction and the Literature Review chapters, the current standards and guidelines provide environmental targets and benchmarks for the use of space. Although the main study was based on a small sample, results may be were compared to those and summarised as follows:

- Environmental targets:
 - Indoor air temperature. The results of both longitudinal studies were outside the bounds of CIBSE recommendations in living rooms but inside these bounds in bedrooms. Also these results were below the 21 °C recommended by Public Health England for living rooms. Results were as follows:
 - * In living room: 19.1 ± 2.2 °C for the pilot, and 18.5 ± 2.7 °C for the main study.
 - * In bedroom: 19.2 ± 1.8 °C for the pilot, and 18.9 ± 2.7 °C for the main study.
 - Indoor relative humidity. The results of both longitudinal studies were inside the bounds of CIBSE recommendations, and described as follows:
 - * In living room: 57 ± 7 % for the pilot, and 54 ± 12 % for the main study.
 - * In bedroom: 58 ± 9 % for the pilot, and 55 ± 13 % for the main study.
 - Local discomfort. Thermal stratification was reviewed for a sub-set of 10 dwellings. Results show that for one half of the sample, temperature difference was greater than 3 °C for 54% of the time.
- Predictive approach:
 - Estimation of activity level. The mean monitored activity levels were as follow: $M = 1.69 \pm 0.74$ met using heart rate monitors, and $M = 1.32 \pm 0.13$ met using ac-

celerometers. These results are both higher than the value of 1.2 met prescribed by EN 15251:2007. Also on average male participants were slightly more active than female participants.

- Estimation of clothing level. The mean monitored clothing levels was as follow: $I_{cl}=0.82\pm0.20$ clo. This result is lower than the value of 1 clo prescribed by EN 15251:2007. Also on average female participants wore warmer clothing ensembles than male participants.
 - Estimation of PMV and PPD. The results of both longitudinal studies were as follows: $PMV=-0.9\pm0.5$ and $PPD=26.5\pm19.8$ % for the pilot study, and $PMV=-0.5\pm0.7$ and $PPD=19.6\pm17.5$ % for the main study. These were outside of the bounds of ISO 7730:2005 category B.
 - Assessing thermal perception. The results of the 7-point scale questionnaires were as follow: 0.36 ± 1.12 for the pilot study and 0.35 ± 1.18 for the main study. These were within the bounds of ISO 7730:2005 category B. Interestingly the corresponding predicted mean votes were lower in both instances. If the predicted index was used to control the heating system, then the required set-point would be overestimated. This might result in both occupants being uncomfortable and an increase in energy demand for heating.
- Adaptive approach:
 - Estimation of activity and clothing levels. Although both variables are not accounted for in the current adaptive model, variability in activity and clothing level, form part of the adaptive processes. Results show very little variation throughout the course of a day. However the same methods of estimation may be employed throughout the course of a year to explore seasonal variations.
 - Developing a mixed-method framework to capture people responses. One of the key results of this research was the identification and quantification of different behaviours using wearable sensors. These methods may be used in future research to establish the probability of occurrence of behaviour.

Finally, to answer the list of research design requirements set out in Chapter 3, all the 'Must Have' items have been achieved, with the addition of the measuring relative air velocity in the main study, and having conditioning-monitoring in the capture of the SenseCam images. However, the study did not use wireless sensing linked to network monitoring systems. This

represents an area for future research studies, with the aim of optimising energy demand while simultaneously supporting occupant comfort.

7.3 Limitations and recommendations for future research

This thesis has highlighted a number of questions to be investigated in future research. These include the following:

- **Confidentiality:** Visual information allowed to validate the sensors monitoring, and confirm or reject inferences made. In other studies collecting images may be an issue, therefore future research may develop wearable sensor kits without a camera. This would require a more thorough calibration process.
- **Sample:** Although the main study sample was well distributed within the sample frame, the number of participants remains relatively small. One of the main barriers remains the volume of monitoring data. The development of the automated segmentation process in this study may allow future research to recruit larger number of participants.
- **Season location and setting:** Although the study was carried out in dwellings during the winter, future research may apply similar methods to gather information on people's responses to warm thermal discomfort. Additionally, this longitudinal approach may be used to investigate seasonal behavioural adaptation.
- **Dynamic thermal environments:** Methods developed in this thesis allow the estimation of personal variables and behaviour change through time. Future research may estimate the probability of occurrence of different responses.

To summarise, the implications and contributions to existing knowledge of this thesis is three-fold. Theoretically, this research introduces a framework to monitor thermal discomfort responses that incorporates a wider range of observed behaviours. Methodologically, this research demonstrates the efficacy of multi-method observational approaches for understanding discomfort responses. Substantively, this research highlights the importance of researchers critical approach when evaluating occupant self-reported behaviour, as this could differ from actual or observed behaviour

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Appendix A

Field studies' forms

A.1 Pilot study's forms

1. Information sheet for participants in research studies
2. Informed consent form for participants in research studies
3. Questionnaire A
4. Questionnaire B
5. Feedback interview - discussion guide
6. Focus group - discussion guide

A.2 Main study's forms

1. Information sheet for participants in research studies
2. Recruiting Email for participants in research studies
3. Informed consent form for participants in research studies
4. Questionnaire
5. Feedback interview - discussion guide
6. Interview - discussion guide

PARTICIPANT INFORMATION SHEET

OCTOBER 2010

Full title of the research project

Mapping and matching mental model of home thermal comfort systems

Researcher contact details

Stephanie Gauthier

UCL Energy Institute, Central house, 14 Upper Woburn Place, London WC1H 0NN

Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

You are being invited to take part in a pilot research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

Although much of the research on heating pattern in dwelling has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field studies results, for instance BS EN ISO standards and ASHRAE standard 55-2004, which set out the experimental frameworks or CIBSE guide A which establishes optimum temperature for comfort.

Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings; from modifying the building fabric to upgrading operating systems. Yet energy consumed in dwelling continues to rise. Occupant's behaviour is one of the main reasons identified for this trend. Consequently it is critical to map-out how a dwelling comfort system is conceptualized and understood by its occupants.

The aims of this pilot study are to:

- Test different methods, used to gather respondent thermal discomfort responses in their home;
- Test different analysis tools, used to investigate collected information.

The pilot study will last for 5 weeks, starting at the end of October and finishing at the beginning of December 2010.

The pilot study is designed to gather recorded and reported information. It consists of a number of six component surveys, outlined below.

Why have I been invited to participate?

The 11 participants have been chosen among friends and colleagues living and working in London. They represent a mix of private tenants and owner-occupiers with different occupancy ratio, from single to multiple occupiers and share dwellings. This sample is not representative of the UK population, yet it provides insights to answer the aim of this pilot study.

Do I have to take part?

This research is entirely voluntary. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What will happen if I take part?

The methods of data collection are explained below.

A/ Visit 1 (1-2h)

The researcher will come to you and bring four elements:

- *Questionnaire*: an interview is first conducted with the householder. The interview topics include household characteristics, satisfaction with the home and the area and work done to the property.
- *Survey*: visual inspection of the property, both internally and externally. Data collected includes for example construction type and details of heating system.
- *Diary*: a SenseCam is handed out, followed by a short introduction on how to use it. This wearable recording device takes photographs when triggered manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared detector and a multiple-axis accelerometer.
- *Monitoring*: two dataloggers to be placed in your living room and bedroom to record the ambient temperature, relative humidity and light intensity.

B/ Recording (3 days)

The first visit is followed by a recording period of three days, when you need to wear the SenseCam. This passive wearable camera is providing a visual diary of your wear-about in your home. If you wish to record a specific event, you can press the manual shutter button. Also if you wish to stop taking picture for a period, the 'privacy' button allows pausing of recording. It is worth pointing out that this device excludes audio recording. If you have any further question(s) please don't hesitate to ask the researcher.

C/ Visit 2 (30min)

Three days after the first visit, the researcher will come to collect the equipments. An additional questionnaire will be complete in a form of semi-structured *Feedback Interview*.

D/ Focus Group (1-2h)

At the end of the study you will be asked to join a focus group. It will take place at UCL Energy Institute, an evening during the week.

What are the possible benefits of taking part?

By taking part in this pilot study you will help the researcher and each participants furthering their understanding of occupant behaviour in home. This will have a direct benefit to the research on the dynamics of energy consumption in dwellings.

Will what I say in this study be kept confidential?

All information collected about the individual will be kept strictly confidential. This will be ensured in the collection, storage and publication of research material by using name coding system and pixellisation of photographs. When used for presentations and publications, imagery material will need addition consent for the participant; illustration will be reviewed image by image.

Data generated by the study must be retained in accordance with the University's policy on Academic Integrity. In the course of the research the data will be kept securely in paper or electronic form. The information will then be deleted/destroyed when no longer required for this research project.

What should I do if I want to take part?

If you would like to take part in the pilot study, please reply to this email stating your availability for the first visit. These will occur on Thursday evening (6-7pm) or Sunday Morning (10-12am). The attached Informed Consent Form will be completed and signed during the first visit.

What will happen to the results of the research study?

The results of the research will be used principally in my up-grade report and presentations, scheduled for January 2011. They should also be used in my thesis, and associated presentations and publications. If you wish to obtain a copy of the published research please contact me in due course.

Who is organising and funding the research?

I am conducting this pilot study as a student at UCL Energy Institute. This research is funded by EPSRC as part of the Doctoral Training Centre in Energy Demand Reduction and the Built Environment.

Who has reviewed the study?

My supervisors, Dr. David Shipworth and Prof. Bob Lowe, have reviewed this research. My Department's Data Protection Co-ordinator, Ms Kim Novelli, also registered it; the associated UCL data protection registration reference number is: No Z6364106/2010/10/39 (section 19, research: social research).

Contact for Further Information

Should you required further information please contact me:

Stephanie Gauthier

UCL Energy Institute, Central house, 14 Upper Woburn Place, London WC1H 0NN

Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

If you have any concerns about the way in which the study has been conducted, you should contact the Department's Ethic and Data Protection Co-ordinator on k.novelli@ucl.ac.uk

Thank you for taking time to read this information sheet.

INFORMED CONSENT FORM

Full title of the project

Mapping and matching mental model of home thermal comfort systems

Researcher contact details

Stephanie Gauthier

UCL Energy Institute, Central house, 14 Upper Woburn Place, London WC1H 0NN

Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

Please Initial Box

1. I hereby agree to **participate** in focus group sessions and in diary recording in connection with the above study. ☐
2. I confirm that I have read and understand the **information sheet** for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the researcher through the above contact details. ☐
3. I understand that my participation in this study is entirely **voluntary** and that I am free to **withdraw** at any time, without giving reason. In the event that I withdraw from the study, recording material of focus group sessions will be kept by the researcher and associated transcript will still be made. ☐
4. I understand that the information provided by me will be held **confidentially**, such that only the researcher can trace this information back to me individually. Name coding system and pixelisation of photos will be used. ☐
5. I understand that the information will be retained for the length of the study and I can have access to it at any time during this period. The information will be **deleted/destroyed** when no longer required for this study. ☐
6. I understand that for **security** reasons, the electronic database will be password protected and paper files will be locked in filing cabinets. ☐
7. I understand that the recordings and its contents belong to the project and that this information can be used by the researcher in **presentations and publications**. However this exclude imagery material which will need addition consent; illustration will be reviewed image by image. ☐

Please Tick Box

Yes

No

8. I agree to the focus group being **audio recorded**. ☐ ☐
9. I agree to have the **diary images viewed** by the researcher and her supervisors only. The information will only be used for research purpose. ☐ ☐

.....
Name of Participant

.....
Date (day/month/year)

.....
Signature

.....
Name of Researcher

.....
Date (day/month/year)

.....
Signature

QUESTIONNAIRE A

Full title of the pilot study

Mapping mental model of home thermal discomfort responses

Serial no label

Participants no

Interviewer

...

...

...

Survey Record

Record date of text reminder

Session date

Start time

Finish time

Location

...

...

...

...

...

Qn b	SHE codes	Show Cards	Topic
ANSI/ASHRAE STANDARD 55-2004 (appendix E)			
1	OutTemp		Please estimate the approximate outside air temperature (°F or °C) ...
2	Sky		Please check the current Sky condition. Clear <input type="checkbox"/> Mixed (Sun & Clouds) <input type="checkbox"/> Overcast <input type="checkbox"/>
3	SeaC		Please check the current Seasonal Conditions Winter <input type="checkbox"/> Spring <input type="checkbox"/> Summer <input type="checkbox"/> Fall <input type="checkbox"/>
4	clo	N6	Looking at this card, how would you describe your clotting? If you are wearing articles of clothing not listed in the table, please enter them into the space provided below. ...
5	act10	N7	Looking at this card, how would you describe your activity level in the last 10min? ...
6	act20	N7	Looking at this card, how would you describe your activity level between 10 and 20 minutes ago? ...
7	act30	N7	Looking at this card, how would you describe your activity level between 20 and 30 minutes ago? ...
8	act60	N7	Looking at this card, how would you describe your activity level between 30 and 60 minutes ago? ...
9	Equip		Please list below the equipment adding or taking away for head load. (i.e. computer, lighting, fans,...)
10	ash		How do you feel at this precise moment? I am... Hot <input type="checkbox"/> Warm <input type="checkbox"/> Slightly warm <input type="checkbox"/> Neutral <input type="checkbox"/> Slightly Cool <input type="checkbox"/> Cool <input type="checkbox"/> Cold <input type="checkbox"/>
EN ISO 10551:2001 (annex B)			
11	comf		Do you find this...? comfortable <input type="checkbox"/> slightly uncomfortable <input type="checkbox"/> uncomfortable <input type="checkbox"/> very uncomfortable <input type="checkbox"/> extremely uncomfortable <input type="checkbox"/>
12	mci		At this moment, would you prefer to be...? much cooler <input type="checkbox"/> cooler <input type="checkbox"/> slightly cooler <input type="checkbox"/> without change <input type="checkbox"/> slightly warmer <input type="checkbox"/> warmer <input type="checkbox"/> much warmer <input type="checkbox"/>
13	tsa		Taking into account your personal preference only, would you accept rather than reject this climatic environment? Yes <input type="checkbox"/> No <input type="checkbox"/>
14	PersTol		Is this environment, in your opinion...? perfectly bearable <input type="checkbox"/> slightly difficult to bear <input type="checkbox"/> fairly difficult to bear <input type="checkbox"/> very difficult to bear <input type="checkbox"/> un-bearable <input type="checkbox"/>
RP-884 Database (appendix E)			
15	vent		At this moment, how is the air movement around you? 6. very acceptable <input type="checkbox"/> 5 <input type="checkbox"/> 4 <input type="checkbox"/> 3 <input type="checkbox"/> 2 <input type="checkbox"/> 1. very unacceptable <input type="checkbox"/>
16	avm		Taking into account your personal preference only, would you change the air movement? more <input type="checkbox"/> no change <input type="checkbox"/> less <input type="checkbox"/>
17	PCC		How do you perceive the control over your thermal environment? 1. no control <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5. complete control <input type="checkbox"/>
18	PCS		How satisfied are you with these controls? 1. very dissatisfied <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6. very satisfied <input type="checkbox"/>

Qn b	SHE codes	Show Cards	Topic
19	PCEC1		Can you open/close windows? Yes <input type="checkbox"/> No <input type="checkbox"/>
20	PCEC2		Can you open/close external doors? Yes <input type="checkbox"/> No <input type="checkbox"/>
21	PCEC4		Can you adjust thermostats? Yes <input type="checkbox"/> No <input type="checkbox"/>
22	PCEC5		Can you adjust curtains/blinds? Yes <input type="checkbox"/> No <input type="checkbox"/>
23	PCEC6		Can you adjust local heaters? Yes <input type="checkbox"/> No <input type="checkbox"/>
24	PCEC7		Can you adjust local fans? Yes <input type="checkbox"/> No <input type="checkbox"/>
25	PCED1		Do you exercise any of these options, open/close windows? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
26	PCED2		Do you exercise any of these options, open/close external doors? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
27	PCED4		Do you adjust thermostats? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
28	PCED5		Do you adjust curtains/blinds? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
29	PCED6		Do you adjust local heaters? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
30	PCED7		Do you adjust local fans? n/a <input type="checkbox"/> Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
			Additional questions
31			Describe your food and liquide intake in the last 10min. ...
32			Describe your food and liquide intake between 10 and 30 minutes ago. ...
33			Describe your food and liquide intake between 30 and 60 minutes ago. ...
			ANSI/ASHRAE STANDARD 55-2004 (appendix E)
34	EnvCom		Please write below any additionnal environment comments. ...
35	OccLoc		Place an 'X' in the approimate place where you most often be.

Survey

- 33 B&Rtype Describe the building & the room type
...
- 34 OutRH Note: Outside Relative Humidity (%)
...
- 35 ThermSet Note: Thermostat Setting (°F or °C)
...
- 36 Hset Note: Humidity Setpoint (%)
...
- 37 OccNb Note: Total Number of Occupant(s)
...

QUESTIONNAIRE B

Full title of the pilot study

Mapping mental model of home thermal discomfort responses

Serial no label

...

Participants no

...

Interviewer

...

Survey Record

Record date of text reminder

...

Session date

...

Start time

...

Finish time

...

Location

...

Qn b	SHE codes	Show Cards	Topic
Household characteristics			
1	Name		What is your name? ...
2	Sex		Gender Male Female
3	Age		What was your age at your last birthday? ...
4	MarStat	N1	From this card, are you... ...
5	LiveWith		Are you living with someone in the household as a couple? Yes No Yes - same sex
6	R	N2	From this card, how the people in the household are related to each other? ...
7	NoUnits		Number of family units ...
8	Ethnic01	H1	From this card, which of these groups do you belong to? ...
9	Ten1	H8	In which of these ways do you occupy this accommodation? ...
Genral Health & Disability			
10			How would you describe your general health level today? (stress, skickness,...) ...
11			How would you describe your general health level in the last 10 days? ...
12	Has441		Do you (or any member of your household) have any long-standing illness, disability or infirmity? By long-standing I mean anything that has troubled him/her for a period of at least 12 months or that is likely to affect him/her over a period of at least 12 months? Yes No
13	Has4412		Does this illness or disability limit your/their activities in any way? Yes No How:...
14	Has442		Does this illness or disability make it necessary to have specially adapted accommodation? Yes No How:...
Economic activity status			
15	EconAct	H50	Looking at this card, how would you describe your situation in the 7 days ending the Sunday of the last week? ...
Housing History			
16	Hlong		How long have you lived at this address? less than 12months 12months-2 years 2-3 years 3-5years 5 years or longer ...
17	HMnths		(less than 12months) How many months have you lived here? ...
18	NoMoves1		(less than 12months) Have you moved more than once in the past year? Yes No
19	NoMoves2		(less than 12months) How many times have you moved in the past year? ...
Accommodation type			
20	Accom		Is the household's accommodation... House/bungalow Flat/maisonette Room/rooms Something else
21	HseType		Is the house/bungalow... Detached Semi-detached Terraced/end of terrace
22	FltTyp		Is the flat/maisonette in... Purpose-built block Converted house Other kind of building
23	YrBult		When was this property built? ...
24	YrBult2	N3	(for 1986...2010) And can I just check the exact yea the property was built? ...
25	NRms		How many type of rooms do you have? Bedrooms Kitchen > 2m wide Kitchen < 2m wide Living room Bathroom Utility & other
26	Shrms		How many rooms are shared with other householders? ...
27	Cheat		Is there central heating in... Living room & bed's) Some of these No central heating
28	Floor		On what floor of this building is your main living accommodation? ...
29	FloorEnt	N4	On what floor of this building is the front door to the flat? ...
30	FIBld	N4	How many floors are there in the whole building? ...

Qn b	SHE codes	Show Cards	Topic
			Renting
31	Llord		Who is your landlord? Local authority Housing association Employer Relative/friend Private landlord Other
32	Furn		Is the accommodation provided... Furnished Partly furnished Unfurnished
33	ResLL		Does the landlord live in the building? Yes No
34	ResLL2		Does the landlod live in the same flat as you? Yes No
35	SmAg		Thinking about all the people in your household, are you all covered by the same renting agreement with your landlord? All, same agreement Some, separate agreement(s)
36	SerInc	TG4	Does the rent include any of these services... ... (If included) How much of the rent is for gas & electricity? ... How much was your last electricity bill? ... How much was your last gas bill? ... How many times a year is this amount paid? ...
41	PHA213	G6	Generally, how satisfied are you with the way your landlord deals with repairs and maintenance? ...
42	PHA213A	TG7	(If dissatisfied) What is the main reason why you are dissatisfied? ...
43	PPrevAc	TG9	Thinking about the accommodation you lived in before moving here, will you please tell me in which of the ways on this card you occupied the accommodation? ...
			Owning
44	Lease		May I just check, do you own the flat... Freehold Common hold / Share-of-freehold Leasehold
45	FrHlder	N5	Is the freehold owned by... ...
46	FrManage		Who manages the property? Is it... Landlord Managing agent Leaseholders
47	MainMaj		Has there been any major maintenance work in the last three years? Yes No Don't know
48		TG4	Does the service charge include any of these services... ... How much was your last electricity bill? ... How much was your last gas bill? ... How many times a year is this amount paid? ...
49			
50			
51			
			Satisfaction with accommodation
52	HSatis	H21	Now I'd like to ask some questions about how satisfied you are with your accommodation and some aspects of your home. How satisfied are you with this accommodation? ...
53	Sattern	H22	Taking everything into account, to what extent do you personally agree that being owner/tenant is a good way of occupying a home? ...

FEEDBACK INTERVIEW FORM

Full title of the pilot study

Mapping mental model of home thermal discomfort responses

Serial no label

Interviewee no

Interviewer

...

...

...

Survey Record

Record date of text
reminder

Visit made

Start time

Finish time

...

...

...

...

Outcome:

Completed interview ☐

Partial interview ☐

Miss appointment ☐

Reason for non-survey /re-schedule: ...

Interview

Based on a 1 to 5 scale, please tick box

1. Overall, how well did your diary collection go?

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very well)

2. What was your first impression of the diary method?

☐ 1 (no interest)

☐ 2

☐ 3

☐ 4

☐ 5 (very interested)

3. How was the introduction to the diary method? (Preparation)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

4. How useful was the user-guide? (Documentation)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very useful)

5. How satisfied are you with the SenseCam device you received? (Method)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

6. How good are SenseCam's controls? (Flexibility)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

7. How do you feel about the timing; is 3 days enough? (Organisation)

☐ 1 (too short)

☐ 2

☐ 3 (about right)

☐ 4

☐ 5 (too long)

Please Tick Box

Yes

No

8. Did you forget to wear your SenseCam?

☐

☐

9. At time, did you forget you were wearing your SenseCam?

☐

☐

10. Did the SenseCam changed the way other occupants acted?

☐

☐

Interview

Did you encounter any privacy concern?

...

Did you encounter any practical issues while using the technology?

...

Did your experience changed overtime?

...

Did you become more/less self-conscious?

...

Interview Conclusion

The section you have just completed may not convey everything you would like to say about the Pilot Study. The comments section below allows you to add supplementary information you wish to express.

10. Additional Comments and Suggestions

Thank you for taking the time to complete this feedback interview.

FOCUS GROUP: DISCUSSION GUIDE

Full title of the pilot study

Mapping mental model of home thermal discomfort responses

<i>Serial no label</i>	<i>Participants no</i>	<i>Moderator</i>	<i>Observer</i>
...

Survey Record

Record date of text reminder	Session made	Start time	Finish time	Location
...

Setting-up	30 min (18:30)
Arrange the room: seating, name tag on table, table plan	
Set-up equipments (2 audio recorders)	
External Observer (Henrietta L.) - to take note of non-verbal response, observer's guide	

Task 1: Introduction	5 min (19:00)
<p>Thank everyone for coming</p> <p>Recording</p> <p style="padding-left: 40px;">to help me remember what everyone says</p> <p style="padding-left: 40px;">is everyone happy to proceed with the recording</p> <p style="padding-left: 40px;">TURN recorder on</p> <p>Introduce self and observer / co-facilitator</p> <p>Ask everyone to introduce themselves:</p> <p style="padding-left: 40px;">surname,</p> <p style="padding-left: 40px;">live in...[Hammersmith],</p> <p style="padding-left: 40px;">in...[a flat part of a Victorian house],</p> <p style="padding-left: 40px;">with...[partner],</p> <p>Explain the nature of the research, 'research is about' :</p> <p style="padding-left: 40px;">Understanding the dynamics of residential energy consumption</p> <p style="padding-left: 40px;">Mapping occupants thermal discomfort responses</p> <p>Explain the objectives of the pilot study:</p> <p style="padding-left: 40px;">to learn - what, when, where - people's thermal discomfort responses</p> <p style="padding-left: 40px;">to test methods to gather information</p> <p>Explain the format of the Focus Group:</p> <p style="padding-left: 40px;">Exploratory research method</p> <p style="padding-left: 40px;">the session will be in 4 parts</p> <p style="padding-left: 40px;">it will be around 1h</p> <p style="padding-left: 40px;">make it enjoyable</p> <p style="padding-left: 40px;">encourage participation & formulation of idea</p> <p>Explain ground rules:</p> <p style="padding-left: 40px;">escape route in case of fire & meeting point</p> <p style="padding-left: 40px;">ethic: confidentiality: no name in final report</p> <p style="padding-left: 40px;">no expectation</p> <p style="padding-left: 40px;">no right or wrong answers</p> <p style="padding-left: 40px;">no talking over each other</p> <p style="padding-left: 40px;">make sure all phone turned off</p> <p>Is everyone clear?</p>	

Task 2: Scenario	10 min (19:05)
<p>Rational:</p> <p style="padding-left: 40px;">Focusing exercise</p> <p style="padding-left: 40px;">To introduce thermal comfort</p> <p style="padding-left: 40px;">To encourage participation</p> <p style="padding-left: 40px;">To assess level of awareness & understanding</p>	
<p>We are going to begin with an activity : 'scenario 1'</p> <p>Each participants will be asked to write down everything they think of when they see picture A.</p> <p>Anything that come to mind: words or pictograms</p> <p>As many as you can in the next 2mins</p> <p>After 2 mins</p> <p>Ask one person to tell the group about one item.</p>	

Write it on the board Q: Did anyone else think of anything similar to that? If yes, write-it near the first one Q: what else did you think off? P: what is your reaction to the picture? Precise, perceived value Go round the group	
---	--

Task 3: Questions	35 min (19:15)
<p>Asking about response to thermal discomfort</p> <p>Q: What is your first actions when coming back home?</p> <p>Q: IN WINTER - If feeling hot or cold in your home, what do you think you could do that would help prevent thermal discomfort?</p> <p>P: IN WINTER - What is your typical response to thermal discomfort?</p> <p>P: IN WINTER - What are the best way to eliviate thermal discomfort?</p> <p>A: List on the board min 10 responses</p> <p>Q: A number of reponses have been mentionned. Think about ...(putting a jumper on)... How do these compare to the other responses already mentioned?</p> <p>Q: Tell us about the circumstances when [A to previous Q, i.e. put on a jumper, open windows] ?</p>	15 min (19:15)
<p>Asking about threshold</p> <p>Let's talk about your personal threshold.</p> <p>Q: If feeling hot or cold in your home, how long do think you wait before acting?</p> <p>P: --aware of being cold--reach a point--act or not?</p> <p>P: Is the response type determined by how long you have been feeling cold? or how wrong the feeling is?</p> <p>Q: What are the characteristics of your threshold to thermal discomfort?</p> <p>P: pysiological or psychological touch: shivering, sweating visual: bleu fingers, watching a room thermostat noise: wind through cheminey, rain on the window</p> <p>Q: What about other people in the household?</p>	10 min (19:30)
<p>Asking about influencing factors</p> <p>Q: Does your response change when other people are in the same room?</p> <p>Q: What is the most influencing factor on your response type/rate?</p> <p>P: In addition how could the following things influence your response: Previous experiences, habit, knowledge, belief Social links (family, friends, community) Personal or financial aim (reduce energy usage)</p>	10 min (19:40)

Task 4: Summary and Conclusion	10 min (19:50)
Rational:	
Reflection - Feedback	
Let's summarise the key point of our discussion ...	
Q: Does this summary sounds complete? Do you have any changes or additions?	
P: The goal is to map people thermal discomfort responses. Have we missed anything?	
P: Are they other factors which influent your thermal comfort we have not yet talk about?	
Q: What did you learn from this session?	
Thank everyone for their time and all their input, and hope you have enjoyed it. What happens next:	
What will happen to the data? Analysis & Reporting Next stages: up-grade report and presentation, 31st Jan	
Hope it was good fun and an iteresting experience	

Debriefing	20 min (20:00)
Take time to:	
Summarise thoughts Discuss with observer Gather equipments & paper, close the room	

Information Sheet for Participants in Research Studies

You will be given a copy of this information sheet.

Title of Project: **Mapping people's responses to thermal discomfort in dwellings in winter**

This study has been approved by the UCL Research Ethics Committee (Project ID Number): 4189/001

Research's Name	Stephanie Gauthier
Work Address	UCL Energy Institute Central house, 14 Upper Woburn Place, London WC1H 0NN
Contact Details	Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

Details of Study

What is the purpose of the study?

Although much of the research on heating pattern in dwelling has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field studies results, for instance BS EN ISO standards 7730 and ASHRAE standard 55, which set out the experimental frameworks or CIBSE guide A which establishes optimum temperature for comfort. Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings; from modifying the building fabric to upgrading operating systems. Yet energy consumed in dwelling continues to rise. Occupants' behaviour is one the main reasons hypothesised for this trend. Consequently it is critical to map-out how a dwelling thermal comfort system is conceptualised and understood by its occupants.

The **aim** of this field study is to:

- Map **how householders respond** to thermal discomfort

The **objectives** of this field study are to:

- Investigate **factors that influence householder's responses** to thermal discomfort, using a multi-method approach to gather and to analyse information.
- Measuring the effect of ambient temperature, clothing and activity level on Predicted Mean Vote (PMV) using a multi-variants probabilistic analysis.

The study will last for 12 weeks, starting mid-October 2012 and finishing mid-December 2012. Using case-study research design 14 dwellings will be monitored over a period of 10 consecutive days each.

Why have I been invited to participate?

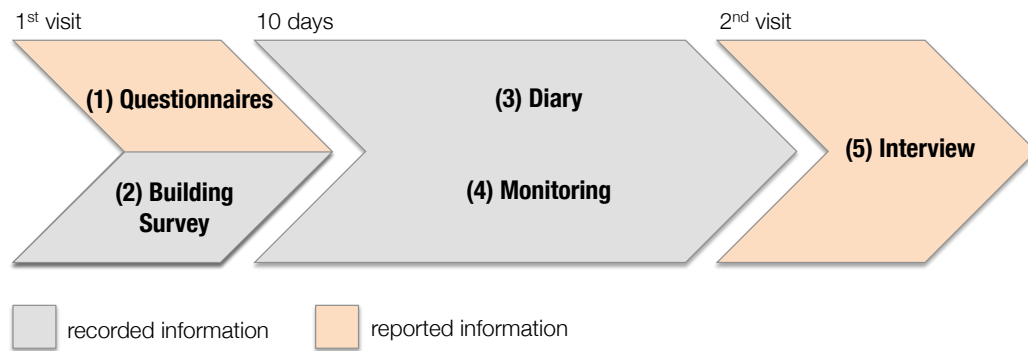
The 14 participants have been chosen among UCL staff members living and working in and around London. They represent individuals of different gender, age and weight, this sample criteria has been chosen to match the criteria set by EN ISO 8996: 2004 - Annex C. This sample is not representative of the UK population, yet it provides insights to answer the aim of this study.

Do I have to take part?

This research is entirely **voluntary**. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason.

What will happen if I take part?

The study is design to gather recorded and reported information. It consists of a five-component survey layout in 3 sequences, outlined below:



A/ 1st Visit (1h)

- **Questionnaire:** a questionnaire is first conducted with the participant. The questionnaire's topics include household characteristics, satisfaction with the home and the area and work done to the property.
- **Building Survey:** visual inspection of the property, both internally and externally. Data collected includes for example construction type and details of the heating system.
- **Diary:** a SenseCam is handed out, followed by a short introduction on how to use this device. Of similar size to a badge, this wearable recording device takes photographs when trigger manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared detector, a multiple-axis accelerometer and a magnetometer. The SenseCam provides two types of outputs: a record of measurements taken by each sensor and a visual diary, but excludes audio recording. Further details on the SenseCam can be found on the manufacturer website: <http://viconrevue.com/> In addition a chest strap and logger will be handed out. This compact device will record heart rate, which will used to evaluate the participants' activity level.
- **Monitoring:** three set of four dataloggers to be placed in the living room and in the bedroom to record ambient temperature and relative humidity. The four dataloggers will be attached to a wooden stand and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by EN ISO 7726:2001. The three wooden sticks will be positioned according to the room layout (cold/warm places) and most likely occupied places. In addition one anemometer will record air velocity and three dataloggers will record ambient temperature and relative humidity in other rooms, depending on how the house is laid-out and used.

B/ Recording (10 days)

The first visit is followed by a recording period of two weeks, when the participants need to wear the SenseCam and the chest-band heart monitor. The passive wearable camera will provide a visual diary of your wear-about in your home. If the participants wish to record a specific event, they can press the manual shutter button. Also if the participants wish to stop taking picture for a period, the 'privacy' button allows pausing of recording. It is worth pointing out that this device excludes audio recording.

C/ 2nd Visit (30min)

Ten days after the first visit, the researcher will come back to the dwelling to collect the equipment and to conduct a short semi-structured interview with the participant, including feedback on the methods employed and their reported typical response to thermal discomfort.

What are the possible benefits of taking part?

By taking part in this study you will help the researcher and each participants furthering their understanding of occupant behaviour in home. This will have a direct benefit to the research on the dynamics of energy consumption in dwellings.

Will what I say in this study be kept confidential?

All information collected about the individual will be kept strictly confidential. This will be ensured in the collection, storage and publication of research material by using name coding system and pixellisation of photographs. When used for presentations and publications, imagery material will need addition consent for the participant; illustration will be reviewed image by image.

Data generated by the study must be retained in accordance with the University's policy on Academic Integrity. In the course of the research the data will be kept securely in paper or electronic form. The information will then be deleted/destroyed when no longer required for this research project.

What should I do if I want to take part?

If you would like to take part in the study, please reply to this email stating your availability for the first visit. These will occur on Wednesday or Thursday. The attached Informed Consent Form will be completed and signed during the first visit.

What will happen to the results of the research study?

The results of the research will be used principally in my thesis and viva, scheduled for September 2013. They should also be used in associated presentations and publications. If you wish to obtain a copy of the published research please contact me in due course.

Who is organising and funding the research?

I am conducting this study as a student at UCL Energy Institute. This research is funded by EPSRC as part of the Doctoral Training Centre in Energy Demand Reduction and the Built Environment.

Who has reviewed the study?

My supervisors, Dr. David Shipworth and Prof. Bob Lowe, have reviewed this research; as well as my Department's Data Protection Co-ordinator, Ms Kim Novelli. The study is registered to UCL Data Protection Registration, under the following registration reference number: no [TBC] (Section 19, research: social research).

Contact for Further Information

Should you required further information please contact me:

Stephanie Gauthier

UCL Energy Institute, Central house, 14 Upper Woburn Place, London WC1H 0NN

Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

If you have any concerns about the way in which the study has been conducted, you should contact the Department's Ethic and Data Protection Co-ordinator on k.novelli@ucl.ac.uk

Please discuss the information above with others if you wish or ask us if there is anything that is not clear or if you would like more information. It is up to you to decide whether to take part or not; choosing not to take part will not disadvantage you in any way. If you do decide to take part you are still free to withdraw at any time and without giving a reason.

All data will be collected and stored in accordance with the Data Protection Act 1998.

Thank you for taking time to read this information sheet.

Recruiting Email for Participants in Research Studies

Message sent on behalf of Stephanie Gauthier, UCL Energy Institute. For further information please use the contact details provided below.

Dear all,

You are being invited to take part in a research study that investigates how people respond to thermal discomfort in their home. This study will use wearable ubiquitous sensor technologies, including SenseCam.

By taking part in this 10-day study you will help the researcher and each participants furthering their understanding of occupant's behaviour in home. This will have a direct benefit to the research on energy demand in dwellings in the UK.

* If you agree to take part, what will happen? *

The researcher will come to your home on a Wednesday or a Thursday to complete a questionnaire and a building survey and to introduce the different sensors. The entire session will last approximately 1 hour. This first visit is followed by a recording period of 10 days. After these 10 days, the researcher will come back to your home to collect the equipment and to complete a short 30 minutes interview.

If you are interested, please send us an email to s.gauthier@ucl.ac.uk; stating:

- . Your name, gender, age and weight as sample criteria;

- . Your availability for the first visit. These will occur on the following days:

October: Wed 10th, Thu 11th, Wed 17th, Thu 18th, Wed 24th, Thu 25th, or Wed 31th;

November: Thu 1st, Wed 7th, Thu 8th, Wed 14th, Thu 15th, Wed 21st, Thu 22nd, Wed 28th, or Thu 29th;

December: Wed 5th, Thu 6th, Wed 12th, or Thu 13th.

Your participation in this study is entirely voluntary and all the information collected will be kept confidential. UCL Data Protection Registration, reference No [TBC], section 19, research: social research.

We would be grateful if you were to take part and forward this message to anyone else how might be willing to do so.

Thank you very much for your help in advance.

Stephanie Gauthier

PhD Student
UCL ENERGY INSTITUTE
Central house, 14 Upper Woburn Place
London WC1H 0NN

s.gauthier@ucl.ac.uk
<http://www.ucl.ac.uk/energy/>
phone: +44 (0)20 3108 5978

Informed Consent Form for Participants in Research Studies

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.

Title of Project: **Mapping people's responses to thermal discomfort in dwellings in winter**

This study has been approved by the UCL Research Ethics Committee (Project ID Number): 4189/001

Research's Name Stephanie Gauthier
Work Address UCL Energy Institute, Central house, 14 Upper Woburn Place, London WC1H 0NN
Contact Details Tel.: +44 (0)20 3108 5978; Email: s.gauthier@ucl.ac.uk

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you. If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you to decide whether to join in. You will be given a copy of this Consent Form to keep and refer to at any time.

Participant's Statement

Please Initial Box

1. I confirm that I have read the notes written above and the **Information Sheet**, and understand what the study involves. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. If I have further queries about the study, I know I can get in touch with the researcher though the above contact details.
2. I understand that my participation in this study is entirely **voluntary** and that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and **withdraw** immediately, without giving reason. In the event that I withdraw from the study, recording material of interview sessions will be kept by the researcher, and associated transcript will still be made.
3. I hereby agree to **participate** in interview sessions and diary recording; and to consent to the processing of my personal information for the purposes of this research study only. I understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the **Data Protection Act 1998**.
4. I understand that the information provided by me will be held **confidentially**, such that only the researcher can trace this information back to me individually. Name coding system and pixelisation of photos will be used.
5. I understand that the information will be retained for the length of the study and I can have access to it at any time during this period. The information will be **deleted/destroyed** when no longer required for this study.
6. I understand that for **security** reasons, the electronic database will be password protected and paper files will be locked in filing cabinets.
7. I understand that the recordings and its contents belong to the project and that this information can be used by the researcher in **presentations and publications**. However this excludes imagery material which will need addition consent; illustration will be reviewed image by image.
8. I agree that the research project named above has been explained to me to my satisfaction and **I agree to take part in this study**.

☐☐☐☐☐☐☐☐

Please Tick Box
Yes No

9. I agree to the interview being **audio recorded**.
10. I agree to have the **diary images viewed** by the researcher and her supervisors only. The information will only be used for research purpose.

☐☐☐☐

.....
Name of Participant

.....
Date (day/month/year)

.....
Signature

.....
Name of Researcher

.....
Date (day/month/year)

.....
Signature

QUESTIONNAIRE

Full title of the research study

Mapping people's responses to thermal discomfort in dwelling

Serial no label

...

Participants no

...

Interviewer

...

Survey Record

Record date of text
reminder

...

Session date

...

Start time

...

Finish time

...

Location

...

No		Code	Show Card	Topic
General information & Health				
1		Name		What is your name? ...
2		Sex		Gender Male Female
3		Age		What was your age, at your last birthday? ...
4		Ethnic	H1	From this card, which of these groups do you belong to? ...
5		Weight	N0	From this card, are you... ...
6				How would you describe your general health level in the last 10 days? ...
7		Has1		Do you (or any member of your household) have any long-standing illness, disability or infirmity? By long-standing I mean anything that has troubled him/her for a period of at least 12 months or that is likely to affect him/her over a period of at least 12 months? Yes No
8		Has2		Does this illness or disability limit your/their activities in any way? Yes No How:...
9		Has3		Does this illness or disability make it necessary to have specially adapted accommodation? Yes No How:...
Economic activity status				
10		EconAct	H50	Looking at this card, how would you describe your situation in the 7 days ending the Sunday of the last week? ...
Household characteristics				
11		Ten	H8	In which of these ways do you occupy this accommodation? ...
12		Hlong		How long have you lived at this address? less than 12months 12months-2 years 2-3 years 3-5years 5 years or longer ...
13		HMnths		(less than 12months) How many months have you lived here? ...
14		NoOcc		Number of occupants ...
15		Re	N2	From this card, how the people in the household are related to each other? ...
Renting				
16	a	Llord		Who is your landlord? Local authority Housing association Employer Relative/friend Private landlord Other
17	a	Furn		Is the accommodation provided... Furnished Partly furnished Unfurnished
18	a	ResLL		Does the landlord live in the building? Yes No
19	a	SerInc	TG4	Does the rent include any of these services... ...
20	a	Ser1		(If included) How much of the rent is for gas & electricity? ...
21	a	Ser2		How much was your last electricity bill? ...
22	a	Ser3		How much was your last gas bill? ...
23	a	Ser4		How many times a year is this amount paid? ...
24	a	PHA1	G6	Generally, how satisfied are you with the way your landlord deals with repairs and maintenance? ...
25	a	PHA2	TG7	(If dissatisfied) What is the main reason why you are dissatisfied? ...
Owning				
26	b	Lease		May I just check, do you own the flat... Freehold Common hold / Share-of-freehold Leasehold
27	b	FrHlder	N5	Is the freehold owned by... ...
28	b	FrManage		Who manages the property? Is it... Landlord Managing agent Leaseholders
29	b	MainMaj		Has there been any major maintenance work in the last three years? Yes No Don't know
30	b	Ser5	TG4	Does the service charge include any of these services... ...
31	b	Ser6		How much was your last electricity bill? ...
32	b	Ser7		How much was your last gas bill? ...
33	b	Ser8		How many times a year is this amount paid? ...
Satisfaction with accommodation				
34		HSatis	H21	Now I'd like to ask some questions about how satisfied you are with your accommodation and some aspects of your home. How satisfied are you with this accommodation? ...

No	Code	Show Card	Topic
ANSI/ASHRAE STANDARD 55-2004 (appendix E)			
35	OutTemp		Please estimate the approximate outside air temperature (°F or °C) ...
36	Sky		Please check the current Sky condition. Clear <input type="checkbox"/> Mixed (Sun & Clouds) <input type="checkbox"/> Overcast <input type="checkbox"/>
37	SeaC		Please check the current Seasonal Conditions Winter <input type="checkbox"/> Spring <input type="checkbox"/> Summer <input type="checkbox"/> Fall <input type="checkbox"/>
38	Ash		How do you feel at this precise moment? I am... Hot <input type="checkbox"/> Warm <input type="checkbox"/> Slightly warm <input type="checkbox"/> Neutral <input type="checkbox"/> Slightly Cool <input type="checkbox"/> Cool <input type="checkbox"/> Cold <input type="checkbox"/>
39	Clo	N6	Looking at this card, how would you describe your clothing? If you are wearing articles of clothing not listed in the table, please enter them into the space provided below. ...
40	Met10	N7	Looking at this card, how would you describe your activity level in the last 10min? ...
41	Met30	N7	Looking at this card, how would you describe your activity level between 10 and 30 minutes ago? ...
42	Food10		Describe your food and liquid intake in the last 10min. ...
43	Food30		Describe your food and liquid intake between 10 and 30 minutes ago. ...
44	Equip		Please list below the equipment adding or taking away for head load. (i.e. computer, lighting, fans,...) ...
EN ISO 10551:2001 (annex B)			
45	Comf		Do you find this...? comfortable <input type="checkbox"/> slightly uncomfortable <input type="checkbox"/> uncomfortable <input type="checkbox"/> very uncomfortable <input type="checkbox"/> extremely uncomfortable <input type="checkbox"/>
46	MCI		At this moment, would you prefer to be...? much cooler <input type="checkbox"/> cooler <input type="checkbox"/> slightly cooler <input type="checkbox"/> without change <input type="checkbox"/> slightly warmer <input type="checkbox"/> warmer <input type="checkbox"/> much warmer <input type="checkbox"/>
RP-884 Database (appendix E)			
47	Va1		At this moment, how is the air movement around you? 6. very acceptable <input type="checkbox"/> 5 <input type="checkbox"/> 4 <input type="checkbox"/> 3 <input type="checkbox"/> 2 <input type="checkbox"/> 1. very unacceptable <input type="checkbox"/>
48	Va2		Taking into account your personal preference only, would you change the air movement? more <input type="checkbox"/> no change <input type="checkbox"/> less <input type="checkbox"/>
49	PCC		How do you perceive the control over your thermal environment? 1. no control <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5. complete control <input type="checkbox"/>
50	PCS		How satisfied are you with these controls? 1. very dissatisfied <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 <input type="checkbox"/> 6. very satisfied <input type="checkbox"/>
51	PCEC1		Can you open/close windows? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
52	PCED1		Do you open/close windows? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
53	PCEC2		Can you open/close external doors? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
54	PCED2		Do you open/close external doors? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
55	PCEC4		Can you adjust thermostats? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
56	PCED4		Do you adjust thermostats? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
57	PCEC5		Can you adjust curtains/blinds? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
58	PCED5		Do you adjust curtains/blinds? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
59	PCEC6		Can you adjust local heaters (i.e. fire place, occasional heater)? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
60	PCED6		Do you adjust local heaters? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
61	PCEC7		Can you adjust local fans? Yes <input type="checkbox"/> No <input type="checkbox"/> N/A <input type="checkbox"/>
62	PCED7		Do you adjust local fans? Never <input type="checkbox"/> Rarely <input type="checkbox"/> Sometimes <input type="checkbox"/> Often <input type="checkbox"/> Always <input type="checkbox"/>
Additional questions			
63	EnvCom		Please write below any additional environment comments. ...

INTERVIEW: DISCUSSION GUIDE

Full title of the pilot study

Mapping people's responses to thermal discomfort in dwelling

<i>Serial no label</i>	<i>Participants no</i>	<i>Moderator</i>	<i>Observer</i>
...

Survey Record

Record date of text reminder	Session made	Start time	Finish time	Location
...

Task 1: Introduction	2 min
<p>Recording</p> <p>to help me remember what everyone says is everyone happy to proceed with the recording TURN recorder on</p> <p>Introduce self and observer / co-facilitator</p> <p>Ask everyone to introduce themselves:</p> <p>surname, live in...[Hammersmith], in...[a flat part of a Victorian house], with...[partner],</p> <p>Explain the nature of the research, 'research is about' :</p> <p>Understanding the dynamics of residential energy consumption Mapping occupants thermal discomfort responses</p> <p>Explain the format of the Interview:</p> <p>Exploratory research method the session will be in 3 parts it will be around 30min encourage participation & formulation of idea</p> <p>Explain ground rules:</p> <p>ethic: confidentiality: no name in final report no expectation no right or wrong answers make sure all phone turned off</p> <p>Is it all clear?</p>	

Task 2: Questions	15min
<p>Asking about response to thermal discomfort</p> <p>Q: What is your first actions when coming back home?</p> <p>Q: IN WINTER - If feeling hot or cold in your home, what do you think you could do that would help prevent thermal discomfort?</p> <p>P: IN WINTER - What is your typical response to thermal discomfort?</p> <p>P: IN WINTER - What are the best way to eliviate thermal discomfort?</p> <p>A: List on the board min 10 responses</p> <p>Q: A number of reponses have been mentionned. Think about ...(putting a jumper on)... How do these compare to the other responses already mentioned?</p> <p>Q: Tell us about the circumstances when [A to previous Q, i.e. put on a jumper, open windows] ?</p> <p>Asking about threshold</p> <p>Let's talk about your personal threshold.</p> <p>Q: If feeling hot or cold in your home, how long do think you wait before acting?</p> <p>P: --aware of being cold--reach a point--act or not?</p> <p>P: Is the response type determined by how long you have been feeling cold?</p> <p>or how wrong the feeling is?</p> <p>Q: What are the characteristics of your threshold to thermal discomfort?</p> <p>P: pysiological or psychological touch: shivering, sweating visual: bleu fingers, watching a room thermostat noise: wind through cheminey, rain on the window</p> <p>Q: What about other people in the household?</p> <p>Asking about influencing factors</p> <p>Q: Does your response change when other people are in the same room?</p> <p>Q: What is the most influencing factor on your response type/rate?</p> <p>P: In addition how could the following things influence your response:</p> <p>Previous experiences, habit, knowledge, belief Social links (family, friends, community) Personal or financial aim (reduce energy usage)</p>	

Task 3: Summary and Conclusion	5 min
<p>Rational:</p> <p>Reflection - Feedback</p> <p>3.1 Reflection</p> <p>Let's summarise the key point of our discussion</p> <p>...</p> <p>Q: Does this summary sounds complete? Do you have any changes or additions?</p> <p>P: The goal is to map people thermal discomfort responses. Have we missed anything?</p> <p>P: Are they other factors which influent your thermal comfort we have not yet talk about?</p> <p>Q: What did you learn from this session?</p> <p>3.2 Feedback</p> <p>Feedback interview form</p>	

Debriefing	5 min
<p>Thank for time and input, and hope you have enjoyed it.</p> <p>What happens next:</p> <p>What will happen to the data? Analysis & Reporting Next stages: up-grade report and presentation, 31st Jan</p> <p>Hope it was good fun and an iteresting experience</p> <p>Gather equipments & paper, close the room</p>	

FEEDBACK INTERVIEW FORM

Full title of the pilot study

Mapping mental model of home thermal discomfort responses

Serial no label

Interviewee no

Interviewer

...

...

...

Survey Record

Record date of text
reminder

Visit made

Start time

Finish time

...

...

...

...

Outcome:

Completed interview ☐

Partial interview ☐

Miss appointment ☐

Reason for non-survey /re-schedule: ...

Interview

Based on a 1 to 5 scale, please tick box

1. Overall, how well did your diary collection go?

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very well)

2. What was your first impression of the diary method?

☐ 1 (no interest)

☐ 2

☐ 3

☐ 4

☐ 5 (very interested)

3. How was the introduction to the diary method? (Preparation)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

4. How useful was the user-guide? (Documentation)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very useful)

5. How satisfied are you with the SenseCam device you received? (Method)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

6. How good are SenseCam's controls? (Flexibility)

☐ 1 (poor)

☐ 2

☐ 3

☐ 4

☐ 5 (very good)

7. How do you feel about the timing; is 10 days enough? (Organisation)

☐ 1 (too short)

☐ 2

☐ 3 (about right)

☐ 4

☐ 5 (too long)

Please Tick Box

Yes

No

8. Did you forget to wear your SenseCam?

☐

☐

9. At time, did you forget you were wearing your SenseCam?

☐

☐

10. Did the SenseCam changed the way other occupants acted?

☐

☐

Interview

Did you encounter any privacy concern?

...

Did you encounter any practical issues while using the technology?

...

Did your experience changed overtime?

...

Did you become more/less self-conscious?

...

Interview Conclusion

The section you have just completed may not convey everything you would like to say about the Pilot Study. The comments section below allows you to add supplementary information you wish to express.

10. Additional Comments and Suggestions

Thank you for taking the time to complete this feedback interview.

Appendix B

Ethic, Data Protection and Risk Assessment application forms

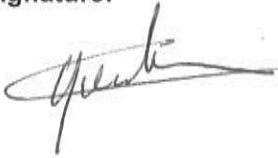
1. UCL Research Ethic Committee - Annual continuing review approval form
2. UCL Research Ethic Committee - Application form
3. Data Protection - Application form (2012-2013)
4. Data Protection - Application form (2012)
5. Data Protection - Application form (2010)
6. Risk Assessment Form



Annual Continuing Review Approval Form

It is a requirement of the UCL Research Ethics Committee that research projects which have received ethical approval by the Committee are monitored annually. Therefore, this form must be completed and returned **PRIOR** to the date that the current approval expires. If your project has ceased or was never initiated, it is still important that you complete this form so that we can ensure that our records are updated accordingly.

1	ID Number: 4189/001 Principal Investigator: Stephanie Gauthier	
2	Project Title: Mapping people's responses to thermal discomfort in dwellings in winter	
3	Current Approval Expires: 31 st March 2013	
4	Project Status: (please tick relevant box) <input type="checkbox"/> Active <input checked="" type="checkbox"/> Terminated	
5	Current Status of Human Participant Use: Beginning date: 25 th October 2012 Date completed (if applicable): 2 nd February 2013 Total Number enrolled to date: 12 participants	
6	Human participants will no longer be used. Please explain: As the research's data-collection is completed, human participants will no longer be used. However the next phase of the research project, data analysis and reporting, should be completed by the end of September 2013.	
7	If funded study, please indicate: Agency: EPSRC Project Period: 01/05/2009 to 31/10/2017 Agency Award Number: EP/H009612/1	
8	Number of participants who withdrew from the project: Please provide reasons for withdrawal: No participants have withdrawn.	

9	Have you modified your research since your last review?	<input type="checkbox"/> Yes	<input checked="" type="checkbox"/> No
If so, you are required to submit a revised application form to the Committee for review.			
10	Please provide with this form a brief report describing the progress of your study thus far.		
Include a description of any adverse or unforeseen circumstances arising out of the research project (e.g. a complaint by a participant, an incident endangering a research worker taking a questionnaire out to a population study, etc) together with a summary of any recent literature, findings, or other relevant information associated with your study.			
Print Name: Stephanie Gauthier		Signature: 	Date: 18/03/2013
FOR OFFICE USE ONLY: <u>Approval</u> The continuing monitoring of this protocol has been reviewed and approved by the Committee. The re-approval date is and is valid for 1 year from this date.			

Please return completed form to:

Secretary of the UCL Research Ethics Committee
Graduate School
North Cloisters, Wilkins Building
Gower Street
London
WC1E 6BT

IMPORTANT: ALL FIELDS MUST BE COMPLETED. THE FORM SHOULD BE COMPLETED IN PLAIN ENGLISH UNDERSTANDABLE TO LAY COMMITTEE MEMBERS.

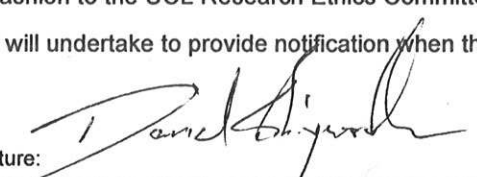
SEE NOTES IN STATUS BAR FOR ADVICE ON COMPLETING EACH FIELD. YOU SHOULD READ THE ETHICS APPLICATION GUIDELINES AND HAVE THEM AVAILABLE AS YOU COMPLETE THIS FORM.

APPLICATION FORM

SECTION A


APPLICATION DETAILS

A1	Project Title: Mapping people's responses to thermal discomfort in dwellings in winter	
	Date of Submission: 28.08.2012	Proposed Start Date: 01.10.2012
	UCL Ethics Project ID Number: 4189/001	Proposed End Date: 31.03.2013
	If this is an application for classroom research as distinct from independent study courses, please provide the following additional details: Course Title: _____ Course Number: _____	

A2	Principal Researcher <i>Please note that a student – undergraduate, postgraduate or research postgraduate cannot be the Principal Researcher for Ethics purposes.</i>	
	Full Name: Dr David Shipworth	Position Held: Reader in Energy & the Built Environment
	Address: UCL Energy Institute Central house, 14 Upper Woburn Place London WC1H 0NN	Email: d.shipworth@ucl.ac.uk
		Telephone: +44 (0)20 3108 5998
		Fax: +44 (0)20 3108 5986
Declaration To be Signed by the Principal Researcher <ul style="list-style-type: none"> ▪ I have met with and advised the student on the ethical aspects of this project design (<i>applicable only if the Principal Researcher is not also the Applicant</i>). ▪ I understand that it is a UCL requirement for both students & staff researchers to undergo Criminal Records Checks when working in controlled or regulated activity with children, young people or vulnerable adults. The required Criminal Record Check Disclosure Number(s) is: N/A ▪ I have obtained approval from the UCL Data Protection Officer stating that the research project is compliant with the Data Protection Act 1998. My Data Protection Registration Number is: TBC (application submitted 28.08.2012) ▪ I am satisfied that the research complies with current professional, departmental and university guidelines including UCL's Risk Assessment Procedures and insurance arrangements. ▪ I undertake to complete and submit the 'Continuing Review Approval Form' on an annual basis to the UCL Research Ethics Committee. ▪ I will ensure that changes in approved research protocols are reported promptly and are not initiated without approval by the UCL Research Ethics Committee, except when necessary to eliminate apparent immediate hazards to the participant. ▪ I will ensure that all adverse or unforeseen problems arising from the research project are reported in a timely fashion to the UCL Research Ethics Committee. ▪ I will undertake to provide notification when the study is complete and if it fails to start or is abandoned. 		
Signature:  Date: 28 Aug 2012		

A3	Applicant(s) Details (if Applicant is not the Principal Researcher e.g. student details):	
	Full Name: Miss Stephanie Gauthier	
	Position Held: PhD Student	
	Address: UCL Energy Institute Central house, 14 Upper Woburn Place London WC1H 0NN	Email: s.gauthier@ucl.ac.uk
		Telephone: +44 (0)20 3108 5978
		Fax: +44 (0)20 3108 5986
	Full Name:	
	Position Held:	
Address:		
Email:		
Telephone:		
Fax:		

A4	Sponsor/ Other Organisations Involved and Funding
	<p>a) Sponsor: <input checked="" type="checkbox"/> UCL <input type="checkbox"/> Other institution</p> <p>If your project is sponsored by an institution other than UCL please provide details:</p>
	<p>b) Other Organisations: If your study involves another organisation, please provide details. Evidence that the relevant authority has given permission should be attached or confirmation provided that this will be available upon request. N/A</p>
	<p>c) Funding: What are the sources of funding for this study and will the study result in financial payment or payment in kind to the department or College? If study is funded solely by UCL this should be stated, the section should not be left blank. The study is funded by UCL as part of the CDT in energy demand, which itself is funded by EPSRC.</p>

A5	Signature of Head of Department or Chair of the Departmental Ethics Committee (This must not be the same signature as the Principal Researcher)	
	<p>I have discussed this project with the principal researcher who is suitably qualified to carry out this research and I approve it. The project is registered with the UCL Data Protection Officer, a formal signed risk assessment form has been completed, and appropriate insurance arrangements are in place. Links to details of UCL's policies on data protection, risk assessment, and insurance arrangements can be found at: http://ethics.grad.ucl.ac.uk/procedures.php</p> <p>UCL is required by law to ensure that researchers undergo a Criminal Record Check if their research project puts them in a position of trust with children under 18 or vulnerable adults. Full details of UCL's policy on criminal record checks can be found at http://www.ucl.ac.uk/hr/docs/criminal_record.php</p> <p>*HEAD OF DEPARTMENT TO DELETE BELOW AS APPLICABLE*</p> <p>I am satisfied that checks: (1) have been satisfactorily completed (2) have been initiated (3) are not required</p> <p>If checks are not required please clarify why below.</p>	
	Print Name: T. ORESZCYN	
	Signature: 	Date: 28/ 8/ 2012
	Chair's Action Recommended: <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	
	<p>A recommendation for Chair's action can be based only on the criteria of minimal risk as defined in the Terms of Reference of the UCL Research Ethics Committee.</p>	

B1

Please provide a brief summary of the project in simple prose outlining the intended value of the project, giving necessary scientific background (*max 500 words*).

Although much of the research on heating pattern in dwelling has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field studies results, for instance BS EN ISO standards 7730 and ASHRAE standard 55, which set out the experimental frameworks or CIBSE guide A which establishes optimum temperature for comfort. Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings; from modifying the building fabric to upgrading operating systems. Yet energy consumed in dwelling continues to rise. Occupants' behaviour is one the main reasons hypothesised for this trend. Consequently it is critical to map-out how a dwelling thermal comfort system is conceptualised and understood by its occupants.

The aim of this field study is to:

- Map how householders respond to thermal discomfort in dwellings in winter

The objectives of this field study are to:

- Investigate factors that influence householder's responses to thermal discomfort, using a multi-method approach to gather and to analyse information.
- Measuring the effect of ambient temperature, clothing and activity level on Predicted Mean Vote (PMV) using a multi-variants probabilistic analysis.

B2

Briefly characterise in simple prose the research protocol, type of procedure and/or research methodology (e.g. observational, survey research, experimental). Give details of any samples or measurements to be taken (*max 500 words*).

The study is design to gather recorded and reported information. It consists of a five-component survey layout in 3 sequences outlined below.

A/ 1st Visit (1h)

- Questionnaire: a questionnaire is first conducted with the participant. The questionnaire's topics include household characteristics, satisfaction with the home and the area and work done to the property.
- Building Survey: visual inspection of the property, both internally and externally. Data collected includes for example construction type and details of the heating system.
- Diary: a SenseCam is handed out, followed by a short introduction on how to use this device. Of similar size to a badge, this wearable recording device takes photographs when trigger manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared detector, a multiple-axis accelerometer and a magnetometer. The SenseCam provides two types of outputs: a record of measurements taken by each sensor and a visual diary, but excludes audio recording. Further details on the SenseCam can be found on the manufacturer website: <http://viconrevue.com/>

In addition a chest strap and logger will be handed out. This compact device will record heart rate, which will used to evaluate the participants' activity level.

- Monitoring: three set of four dataloggers to be placed in the living room and in the bedroom to record ambient temperature and relative humidity. The four dataloggers will be attached to a wooden stand and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by EN ISO 7726:2001. The three wooden sticks will be positioned according to the room layout (cold/warm places) and most likely occupied places. In addition one anemometer will record air velocity and three dataloggers will record ambient temperature and relative humidity in other rooms, depending on how the house is laid-out and used.

	<p>B/ Recording (10 days)</p> <p>The first visit is followed by a recording period of two weeks, when the participants need to wear the SenseCam and the chest-band heart monitor. The passive wearable camera will provide a visual diary of your wear-about in your home. If the participants wish to record a specific event, they can press the manual shutter button. Also if the participants wish to stop taking picture for a period, the 'privacy' button allows pausing of recording. It is worth pointing out that this device excludes audio recording.</p> <p>C/ 2nd Visit (30min)</p> <p>Ten days after the first visit, the researcher will come back to the dwelling to collect the equipment and to conduct a short semi-structured interview with the participant, including feedback on the methods employed and their reported typical response to thermal discomfort.</p> <p><i>Attach any questionnaires, psychological tests, etc. (a standardised questionnaire does not need to be attached, but please provide the name and details of the questionnaire together with a published reference to its prior usage).</i></p>
<p>B3</p>	<p>Where will the study take place (please provide name of institution/department)? If the study is to be carried out overseas, what steps have been taken to secure research and ethical permission in the study country? Is the research compliant with Data Protection legislation in the country concerned or is it compliant with the UK Data Protection Act 1998?</p> <p>The data gathering will take place at the participants' home, and the data analysis at UCL energy Institute.</p>
<p>B4</p>	<p>Have collaborating departments whose resources will be needed been informed and agreed to participate? <i>Attach any relevant correspondence.</i></p> <p>N/A</p>
<p>B5</p>	<p>How will the results be disseminated, including communication of results with research participants?</p> <p>The results of the research will be used principally in the PhD thesis and the viva scheduled for September 2013. They should also be used in associated presentations and publications. A copy of the published research, will be made available to the participant on request.</p>
<p>B6</p>	<p>Please outline any ethical issues that might arise from the proposed study and how they are be addressed. Please note that all research projects have some ethical considerations so do not leave this section blank.</p> <p>The information gathered during the study may included information that the participant do not wish to share. This may include comments made during the questionnaire and the interview and images taken by the SenseCam. To address these issues, full disclosure of all the information collected will be made available to the participant for him/her to review and to decide rather to keep it or not. In addition while gathering visual information, the participant may wish to stop taking picture for a period, then three options are available: (1) the 'privacy' button allows pausing of recording, (2) the camera can be covered using the provided cap, and (3) the device can be turned off.</p> <p>All information collected about the individual will be kept strictly confidential. This will be ensured in the collection, storage and publication of research material by using name coding system and pixellisation of photographs. When used for presentations and publications, imagery material will need addition consent from the participant; illustration will be reviewed image by image.</p> <p>Data generated by the study must be retained in accordance with the University's policy on Academic Integrity. In the course of the research the data will be kept securely in paper or electronic form. The information will then be deleted/destroyed when no longer required for this research project.</p>

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SECTION C

DETAILS OF PARTICIPANTS

C1	Participants to be studied <table border="1" style="margin-top: 10px;"> <tr> <td>C1a. Number of volunteers:</td> <td>14</td> </tr> <tr> <td>Upper age limit:</td> <td>60</td> </tr> <tr> <td>Lower age limit:</td> <td>20</td> </tr> </table> <p>C1b. Please justify the age range and sample size:</p> <p>The sample criteria has been chosen to match the criteria set by EN ISO 8996: 2004 - Annex C, as gender, age (20 to 60 years) and weight (50 to 90kg).</p>	C1a. Number of volunteers:	14	Upper age limit:	60	Lower age limit:	20
C1a. Number of volunteers:	14						
Upper age limit:	60						
Lower age limit:	20						

C2	<p>If you are using data or information held by a third party, please explain how you will obtain this. You should confirm that the information has been obtained in accordance with the UK Data Protection Act 1998.</p> <p>N/A</p>
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C3	<p>Will the research include children or vulnerable adults such as individuals with mental health problems or with learning disabilities, the elderly, prisoners or young offenders? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>How will you ensure that participants in these groups are competent to give consent to take part in this study? <i>If you have relevant correspondence, please attach it.</i></p>
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C4	<p>Will payment or any other incentive, such as gift service or free services, be made to any research participant?</p> <p><input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>If yes, please specify the level of payment to be made and/or the source of the funds/gift/free service to be used.</p> <p>Please justify the payment/other incentive you intend to offer.</p>
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C5**Recruitment**

(i) Describe how potential participants will be identified:

Participants will be part of UCL staff, living in London and fulfil the sample criteria, as gender, age and weight.

(ii) Describe how potential participants will be approached:

The potential participants will be approached by email.

(iii) Describe how participants will be recruited:

After receiving the introductory email, and if interested in taking part the participant may reply stating their availability for the first visit.

Attach recruitment emails/adverts/webpages. A data protection disclaimer should be included in the text of such literature.

C6

Will the participants participate on a fully voluntary basis?

☒ Yes ☐ No

Will UCL students be involved as participants in the research project?

☐ Yes ☒ No

If yes, care must be taken to ensure that they are recruited in such a way that they do not feel any obligation to a teacher or member of staff to participate.

Please state how you will bring to the attention of the participants their right to withdraw from the study without penalty?

The participants' right to withdraw from the study without penalty will be highlighted in the information sheet, the consent form and during the first visit.

C7**CONSENT**

Please describe the process you will use when seeking and obtaining consent.

First the introductory email will highlight the aim of the research, what will happen if the participant agrees to take part, and arrangements for ensuring confidentiality and compliance with the Data protection Act.

Then the information sheet will reiterate the above and underline that the research is entirely voluntary. If the participant do decide to take part he/she will be asked to sign a consent form.

During the first visit the consent form will be reviewed and signed by both parties, as the researcher and the participant.

A copy of the participant information sheet and consent form must be attached to this application. For your convenience proformas are provided in C10 below. These should be filled in and modified as necessary.

In cases where it is not proposed to obtain the participants informed consent, please explain why below.

N/A

8

Will any form of deception be used that raises ethical issues? If so, please explain.

N/A

C9	<p>Will you provide a full debriefing at the end of the data collection phase? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No</p> <p>If 'No', please explain why below.</p>
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C10	<p>Information Sheets And Consent Forms</p> <p>A poorly written Information Sheet(s) and Consent Form(s) that lack clarity and simplicity frequently delay ethics approval of research projects. The wording and content of the Information Sheet and Consent Form must be appropriate to the age and educational level of the research participants and clearly state in simple non-technical language what the participant is agreeing to. Use the active voice e.g. "we will book" rather than "bookings will be made". Refer to participants as "you" and yourself as "I" or "we". An appropriate translation of the Forms should be provided where the first language of the participants is not English. If you have different participant groups you should provide Information Sheets and Consent Forms as appropriate (e.g. one for children and one for parents/guardians) using the templates below. Where children are of a reading age, a written Information Sheet should be provided. When participants cannot read or the use of forms would be inappropriate, a description of the verbal information to be provided should be given. Please ensure that you trial the forms on an age-appropriate person before you submit your application.</p>
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SECTION D	DETAILS OF RISKS AND BENEFITS TO THE RESEARCHER AND THE RESEARCHED
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D1	<p>Have UCL's Risk Assessment Procedures been followed? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No</p> <p>If No, please explain.</p>
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D2	<p>Does UCL's insurer need to be notified about your project before insurance cover can be provided? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p><i>The insurance for all UCL studies is provided by a commercial insurer. For the majority of studies the cover is automatic. However, for a minority of studies, in certain categories, the insurer requires prior notification of the project before cover can be provided. For example, you will need to complete an insurance registration form for the following types of studies: clinical trials which use drugs or vaccines; trials of medical devices; studies which use radiation, surgery or anesthesia as the intervention; studies which will enroll over 5000 subjects.</i></p> <p>If Yes, please provide confirmation that the appropriate insurance cover has been agreed. Please attach your UCL insurance registration form and any related correspondence.</p>
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D3

Please state briefly any precautions being taken to protect the health and safety of researchers and others associated with the project (as distinct from the research participants).

The research's field work has low risk associated to it, to this effect UCL risk assessment form has been completed and associated procedure followed. Even though the participants will be part of UCL staff, the following contact arrangement procedure will be followed:

1. Visit log to be issued before each visit to the department's designated person (DDP), including participant details;
 2. Contact arrangement procedure via mobile phone text to be followed, as:
 - 2.1 the researcher will text the DDP upon arrival;
 - 2.2 the researcher will set an alarm and text the DDP 1.5h after arrival:
 - 2.2.1 to confirm that the visit did finish and that all is fine;
 - 2.2.2 to extend the visit time by 1h;
 - 2.3 if the visit was extended, the researcher will set an alarm and text the DDP 2.5h after arrival:
 - 2.3.1 to confirm that the visit did finish and that all is fine;
 - 2.3.2 to extend the visit time by 1h;
- (step 2.3 may be repeated until the visit finishes)

D4

Will these participants participate in any activities that may be potentially stressful or harmful in connection with this research? ☐ Yes ☒ No

If Yes, please describe the nature of the risk or stress and how you will minimise and monitor it.

D5

Will group or individual interviews/questionnaires raise any topics or issues that might be sensitive, embarrassing or upsetting for participants?

If Yes, please explain how you will deal with this.

No

D6	<p>Please describe any expected benefits to the participant.</p> <p>By taking part in this study the participant will help the researcher and each participants furthering their understanding of occupant behaviour in home. This will have a direct benefit to the research on the dynamics of energy consumption in dwellings.</p>
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D7	<p>Specify whether the following procedures are involved:</p> <p>Any invasive procedure(s) <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>Physical contact <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>Any procedure(s) that may cause mental distress <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>Please state briefly any precautions being taken to protect the health and safety of the research participants.</p> <p>To follow UCL risk assessment form, in case of emergencies the researcher's contact details are given in the introductory email and information sheet. The monitoring equipment have proprietary manufacturer's warranties and do not hold any foreseeable risks, discomforts and inconvenience. During the first visit the participants will be advised of the correct use of the equipment, in addition user's guides will be handed over to the participants.</p>
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D8	<p>Does the research involve the use of drugs? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>If Yes, please name the drug/product and its intended use in the research and then refer to Appendix I</p> <p>Does the project involve the use of genetically modified materials? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>If Yes, has approval from the Genetic Modification Safety Committee been obtained for work? <input type="checkbox"/> Yes <input type="checkbox"/> No</p> <p>If Yes, please quote the Genetic Modification Reference Number:</p>
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D9	<p>Will any non-ionising radiation be used on the research participant(s)? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No</p> <p>If Yes, please refer to Appendix II.</p>
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CHECKLIST

Please submit either 12 copies (1 original + 11 double sided photocopies) of your completed application form for full committee review or 3 copies (1 original + 2 double sided copies) for chair's action, together with the appropriate supporting documentation from the list below to the UCL Research Ethics Committee Administrator. You should also submit your application form electronically to the Administrator at: ethics@ucl.ac.uk

Documents to be Attached to Application Form (if applicable)	Ticked if attached	Tick if not relevant
Section B: Details of the Project		
• Questionnaire(s) / Psychological Tests	<input checked="" type="checkbox"/>	<input type="checkbox"/>
• Relevant correspondence relating to involvement of collaborating department/s and agreed participation in the research.	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Section C: Details of Participants		
• Parental/guardian consent form for research involving participants under 18	<input type="checkbox"/>	<input checked="" type="checkbox"/>
• Participant/s information sheet	<input checked="" type="checkbox"/>	<input type="checkbox"/>
• Participant/s consent form/s	<input checked="" type="checkbox"/>	<input type="checkbox"/>
• Advertisement	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Section D: Details of Risks and Benefits to the Researcher and the Researched		
• Insurance registration form and related correspondence	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Appendix I: Research Involving the Use of Drugs		
• Written signed statement from the pharmaceutical/industrial company stating their agreement to abide by the guidelines on compensation of the Association of British Pharmaceutical Industry (ABPI) or other insurance certificate	<input type="checkbox"/>	<input checked="" type="checkbox"/>
• Proposed volunteer contract	<input type="checkbox"/>	<input checked="" type="checkbox"/>
• Full declaration of financial or direct interest	<input type="checkbox"/>	<input checked="" type="checkbox"/>
• Copies of certificates: CTA etc...	<input type="checkbox"/>	<input checked="" type="checkbox"/>
• Relevant correspondence relating to agreed arrangements for dispensing with the pharmacy	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Appendix II: Use of Non-Ionising Radiation		

Please note that correspondence regarding the application will normally be sent to the Principal Researcher and copied to other named individuals.

Application for inclusion of a research project

All sections must be completed before submitting this form to the data protection team.

All research projects using personal data must be registered with the UCL Data Protection Officer **before the data is collected**. This includes projects approved by the Joint UCL, UCLH and Royal Free Biomedical Research Unit.

It is rarely necessary to store electronic personal data on portable devices such as laptops, USB flash drives, portable hard drives, CDs, DVDs, or any computer not owned by UCL. Similarly, manual personal data should not be regularly removed from UCL premises. In the case of electronic data, to minimise the risk of loss or disclosure, a secure remote connection to UCL should be used wherever possible.

The UCL Computer Security Team has published guidance on the storage of sensitive data on portable devices and media which is available at <http://www.ucl.ac.uk/cert/GuidanceStorageSensitiveData.html> .

If storing sensitive data on portable devices or media all data must be strongly encrypted. ADS general encryption guidance is available at <http://www.ucl.ac.uk/isd/staff/ads/help/guides/encryption> .

Manual personal data and portable electronic devices should be stored in locked units, and they should not be left on desks overnight or in view of third parties.

Anonymised data Projects using anonymised data do not have to be registered with the Data Protection Team and you do not have to worry about compliance with the Act.

Data is only truly anonymised if it is impossible to identify subjects from that information and, if relevant, any other information that UCL holds. For example, if you have a list of research subjects and anonymise it by giving each one a number, but keep a list of the numbers with the names of the subjects, the information has not been anonymised. In this case, it is personal data, and the project must be registered with the Data Protection Team.

Approval We may have some questions about the information you provide, but you will normally be provided with a registration number within a week of submitting the form. However, the period leading up to meetings of the Ethics Committee is always very busy, and you should allow more time for your application to be processed. It is therefore very important to check in good time whether you need to register your project.

Please note that Data Protection Registration numbers will **NOT** be issued when you submit an application form in person to the Data Protection Team.

Please submit this form electronically and send to data-protection@ucl.ac.uk with copies of any information sheets and consent forms that you are using.

UCL Data Protection website

http://www.ucl.ac.uk/finance/legal_services/data_protection/data_protection.php

Any queries regarding this form please contact 020 3108 3128 (internal extension 53128)

This form will be returned to you with the appropriate registration number, which you may quote on your Ethics Application Form, or any other related forms.

Application for inclusion of a research project Form 2

A. APPLICATION DETAILS

A1	Project Title: Mapping people's responses to thermal discomfort in dwelling in winter	
	Date of Submission: 28.08.2012	Proposed Start Date: 01.10.2012
	UCL Ethics Project ID Number: 4189/001	Proposed End Date: 31.03.2013

A2	Principal Researcher <i>(Please note that a student – undergraduate, postgraduate or research postgraduate cannot be the Principal Researcher for Ethics purposes).</i>	
	Full Name: Dr David Shipworth	
	Position Held: Reader in Energy and the Built Environment	
	Address: UCL Energy Institute	
	Central House, 14 Upper Woburn Place	Email: d.shipworth@ucl.ac.uk
	London WC1H 0NN	Telephone: 020 3108 5998

A3	Data Collector(s) Details <i>(if Applicant is not the Principal Researcher e.g. student details):</i>	
	Full Name: Stephanie Gauthier	
	Position Held: PhD Student	
	Address: UCL Energy Institute	
	Central House, 14 Upper Woburn Place	Email: s.gauthier@ucl.ac.uk
	London WC1H 0NN	Telephone: 020 3108 5978

B. DETAILS OF THE PROJECT

B1	<p>Please provide a brief summary of the project</p> <p>Although much of the research on heating pattern in dwelling has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field studies results, for instance BS EN ISO standards 7730 and ASHRAE standard 55, which set out the experimental frameworks or CIBSE guide A which establishes optimum temperature for comfort. Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings; from modifying the building fabric to upgrading operating systems. Yet energy consumed in dwelling continues to rise. Occupants' behaviour is one the main reasons hypothesised for this trend. Consequently it is critical to map-out how a dwelling thermal comfort system is conceptualized and understood by its occupants.</p> <p>The aim of this field study is to:</p> <ul style="list-style-type: none"> • Map how householders respond to thermal discomfort in dwelling in winter. <p>The objectives of this field study are to:</p> <ul style="list-style-type: none"> • Investigate factors that influence householder's responses to thermal discomfort, using a multi-method approach to gather and to analyse information. • Measuring the effect of ambient temperature, clothing and activity level on Predicted Mean Vote (PMV) using a multi-variants probabilistic analysis.
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C. DETAILS OF PARTICIPANTS

C1	<p>Data subjects Who will the personal data be collected from?</p> <p>The participants will be recruited via email through the UCL network and fall into the category of ‘survey respondents’.</p> <p>Following the results of the pilot study carried out in winter 2010/2011, the research’s main field study is focusing on two factors that influence householder’s responses to thermal discomfort:</p> <ul style="list-style-type: none"> • Thermal insulation of clothing; • Activity level, which can be evaluated by measuring the heart rate as a function of the gender, the age and the weight of the subject as defined in EN ISO 8996:2004. <p>The sample frame is therefore defined by these three variables; gender, age and weight.</p>
C2	<p>What data will be collected Please provide details of the type of personal data to be collected</p> <p>The data collection method will include:</p> <ul style="list-style-type: none"> • Questionnaires: an interview is first conducted with the participant. The interview topics include two questionnaires using recognized templates. The first questionnaire addressed socio-demographic variables, using the questions taken from the Survey of English Housing 2007/8 (DCLG, 2010). The second questionnaire focused on thermal environmental variables, using a combination of standard questions from ASHRAE standard 55- 2004, from BS EN ISO 10551:2001 and from RP-884 database. • Building Survey: visual inspection of the property, both internally and externally. Data collected includes for example construction type and details of heating system. • Automatic Diary: a SenseCam is handed out, followed by a short introduction on how to use it. This wearable recording device takes photographs when trigger manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared infrared detector, a multiple-axis accelerometer and a magnetometer. In addition a chest-strap and logger will be handed out. This compact device will record heart rate. • Environmental Monitoring: three sets of four dataloggers to be placed in the living room and in the bedroom to record ambient temperature, relative humidity and light intensity. The four dataloggers will be attached to a wooden post and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by EN ISO 7726:2001. The three wooden posts will be positioned according to the room layout (cold/warm places) and most likely occupied places. In addition three dataloggers will record the same environmental variables in other rooms, depending on how the house is laid-out and used. • Interview: ten day after the first visit, the researcher will come back to the dwelling to collect the equipment and to conduct a semi-structured interview with the participant. It will gather reported information on factors that influence the householder’s responses to thermal discomfort. <p>The personal data to be collected will include:</p> <ul style="list-style-type: none"> • Identification data: personal identifiers; • Personal characteristics: personal details, physical description, disabilities, habits, personality/character; • Family circumstances; • Social circumstances: accommodation, property, professions, travel, leisure activities, lifestyle; • Qualification and skills.

C3	<p>Disclosure Who will the results of your project be disclosed to?</p> <p>The results of the research will be disclosed to the data subject themselves.</p>
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D. CONSENT

D1	<p>Consent Please include the information sheet and consent forms you will be using for this project, and or protocol</p> <p>Please find attached the information sheet and the consent form.</p>
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E. INTERNATIONAL TRANSFER

E1	<p>International Transfer</p> <p>The eighth principle of the Data Protection Act 1998 prohibits the transfer of personal data to countries or territories outside the European Economic Area (which consists of the 27 EU member states, Iceland, Liechtenstein and Norway).</p> <p>At the time of writing the following countries have also been deemed adequate for the purposes of the 8th principle Argentina, Canada, Guernsey, Isle of Man, Jersey and Switzerland.</p> <p>If you intend to transfer data to a country not mentioned above, please supply details of adequate safeguards below:</p> <p>N/A</p>
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F. PUBLICATION

Will the results of your research be published in an academic journal or other publication? **YES** / NO

Please note that published results must not contain data by which an individual can be identified.

The results of the research will be used principally in the thesis and viva, scheduled for September 2013. They should also be used in associated presentations and publications.

All information collected about the individual will be kept strictly confidential. This will be ensured in the collection, storage and publication of research material by using name coding system and pixellisation of photographs. When used for presentations and publications, imagery material will need addition consent for the participant; illustration will be reviewed image by image.

G. NOTIFICATION

G1	Notification (Please note that notification is a prerequisite for registration)
	Have you informed your department's Data Protection Coordinator about your project? YES/NO Contact: Ms Kim Novelli The research project started in September 2009 and will be completed in September 2013.

G2	Notification (Please note that notification is a prerequisite for registration)
	Have you informed your department's computer representative about your project? YES/NO Contact: Mr Simon Buller The data will be stored in paper files and electronic database. This will be held on UCL laptop and associated back-up storages. All these devices are password protected.

H. ETHICS

H1	Are you applying to the UCL Research Ethics Committee? YES/NO Date of Ethics meeting: 17 September 2012
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I. REGISTRATION

I1	Registration: Office use only:	
	UCL Data Protection Registration Number:	Data issued:

Further information

For more information and guidance on the UCL Research Committee, please visit
<http://ethics.grad.ucl.ac.uk/>

When all essential documents are ready to archive, contact the UCL Records Office by email at
records.office@ucl.ac.uk to arrange ongoing secure storage of your research records unless you have made specific alternative arrangements with your department, or funder.

For information on the UCL Records Management Service, please visit
<http://www.ucl.ac.uk/efd/recordsoffice/policy/records-transfer>

Application for inclusion of a research project

All sections must be completed before submitting this form to the data protection team.

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Please submit this form electronically and send to data-protection@ucl.ac.uk with copies of any information sheets and consent forms that you are using.

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Any queries regarding this form please contact 020 3108 3128 (internal extension 53128)

This form will be returned to you with the appropriate registration number, which you may quote on your Ethics Application Form, or any other related forms.

Application for inclusion of a research project Form 2

A. APPLICATION DETAILS

A1	Project Title: Mapping people's responses to thermal discomfort in dwelling	
	Date of Submission: 05.01.2012	Proposed Start Date: 11.01.2012
	UCL Ethics Project ID Number: N/A	Proposed End Date: 30.04.2012

A2	Principal Researcher <i>(Please note that a student – undergraduate, postgraduate or research postgraduate cannot be the Principal Researcher for Ethics purposes).</i>	
	Full Name: Dr David Shipworth	
	Position Held: Reader in Energy and the Built Environment	
	Address: UCL Energy Institute	
	Central House, 14 Upper Woburn Place	Email: d.shipworth@ucl.ac.uk
	London WC1H 0NN	Telephone: 020 3108 5998

A3	Data Collector(s) Details <i>(if Applicant is not the Principal Researcher e.g. student details):</i>	
	Full Name: Stephanie Gauthier	
	Position Held: PhD Student	
	Address: UCL Energy Institute	
	Central House, 14 Upper Woburn Place	Email: s.gauthier@ucl.ac.uk
	London WC1H 0NN	Telephone: 020 3108 5978

B. DETAILS OF THE PROJECT

B1	<p>Please provide a brief summary of the project</p> <p>Although much of the research on heating pattern in dwelling has focused on achieving thermal comfort, less is understood about the way occupants form their responses. Existing approaches are based on climate chamber and field studies results, for instance BS EN ISO standards 7730 and ASHRAE standard 55, which set out the experimental frameworks or CIBSE guide A which establishes optimum temperature for comfort. Recent international agreements on reducing energy consumption have led to a series of interventions in residential buildings; from modifying the building fabric to upgrading operating systems. Yet energy consumed in dwelling continues to rise. Occupants' behaviour is one the main reasons hypothesised for this trend. Consequently it is critical to map-out how a dwelling thermal comfort system is conceptualized and understood by its occupants.</p> <p>The aim of this field study is to:</p> <ul style="list-style-type: none"> • Map how householders respond to thermal discomfort <p>The objectives of this field study are to:</p> <ul style="list-style-type: none"> • Investigate factors that influence householder's responses to thermal discomfort, using a multi-method approach to gather and to analyse information. • Measuring the effect of ambient temperature, clothing and activity level on Predicted Mean Vote (PMV) using a multi-variants probabilistic analysis.
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C. DETAILS OF PARTICIPANTS

C1	<p>Data subjects Who will the personal data be collected from?</p> <p>The participants will be recruited via email through the UCL network and fall into the category of ‘survey respondents’.</p> <p>Following the results of the pilot study carried out in winter 2010/2011, the research’s main field study is focusing on two factors that influence householder’s responses to thermal discomfort:</p> <ul style="list-style-type: none"> • Thermal insulation of clothing; • Activity level, which can be evaluated by measuring the heart rate as a function of the gender, the age and the weight of the subject as defined in EN ISO 8996:2004. <p>The sample frame is therefore defined by these three variables; gender, age and weight.</p>
C2	<p>What data will be collected Please provide details of the type of personal data to be collected</p> <p>The data collection method will include:</p> <ul style="list-style-type: none"> • Questionnaires: an interview is first conducted with the participant. The interview topics include two questionnaires using recognized templates. The first questionnaire addressed socio-demographic variables, using the questions taken from the Survey of English Housing 2007/8 (DCLG, 2010). The second questionnaire focused on thermal environmental variables, using a combination of standard questions from ASHRAE standard 55- 2004, from BS EN ISO 10551:2001 and from RP-884 database. • Building Survey: visual inspection of the property, both internally and externally. Data collected includes for example construction type and details of heating system. • Automatic Diary: a SenseCam is handed out, followed by a short introduction on how to use it. This wearable recording device takes photographs when trigger manually and automatically by timer or by changes in sensors readings. It incorporates a temperature sensor, a light intensity and light-colour sensor, a passive infrared infrared detector, a multiple-axis accelerometer and a magnetometer. In addition a chest strap and logger will be handed out. This compact device will record heart rate. • Environmental Monitoring: three sets of four dataloggers to be placed in the living room and in the bedroom to record ambient temperature, relative humidity and light intensity. The four dataloggers will be attached to a wooden post and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirements set by EN ISO 7726:2001. The three wooden posts will be positioned according to the room layout (cold/warm places) and most likely occupied places. In addition three dataloggers will record the same environmental variables in other rooms, depending on how the house is laid-out and used. • Interview: ten day after the first visit, the researcher will come back to the dwelling to collect the equipment and to conduct a semi-structured interview with the participant. It will gather reported information on factors that influence the householder’s responses to thermal discomfort. <p>The personal data to be collected will include:</p> <ul style="list-style-type: none"> • Identification data: personal identifiers; • Personal characteristics: personal details, physical description, disabilities, habits, personality/character; • Family circumstances; • Social circumstances: accommodation, property, professions, travel, leisure activities, lifestyle; • Qualification and skills.

C3	<p>Disclosure Who will the results of your project be disclosed to?</p> <p>The results of the research will be disclosed to the data subject themselves.</p>
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D. CONSENT

D1	<p>Consent Please include the information sheet and consent forms you will be using for this project, and or protocol</p> <p>Please find attached the information sheet and the consent form.</p>
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E. INTERNATIONAL TRANSFER

E1	<p>International Transfer</p> <p>The eighth principle of the Data Protection Act 1998 prohibits the transfer of personal data to countries or territories outside the European Economic Area (which consists of the 27 EU member states, Iceland, Liechtenstein and Norway).</p> <p>At the time of writing the following countries have also been deemed adequate for the purposes of the 8th principle Argentina, Canada, Guernsey, Isle of Man, Jersey and Switzerland.</p> <p>If you intend to transfer data to a country not mentioned above, please supply details of adequate safeguards below:</p> <p>N/A</p>
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F. PUBLICATION

Will the results of your research be published in an academic journal or other publication? **YES** / NO

Please note that published results must not contain data by which an individual can be identified.

The results of the research will be used principally in the thesis and viva, scheduled for September 2013. They should also be used in associated presentations and publications.

All information collected about the individual will be kept strictly confidential. This will be ensured in the collection, storage and publication of research material by using name coding system and pixellisation of photographs. When used for presentations and publications, imagery material will need addition consent for the participant; illustration will be reviewed image by image.

G. NOTIFICATION

G1	Notification (Please note that notification is a prerequisite for registration)
	Have you informed your department's Data Protection Coordinator about your project? YES/NO Contact: Ms Kim Novelli The research project started in September 2009 and will be completed in September 2013.

G2	Notification (Please note that notification is a prerequisite for registration)
	Have you informed your department's computer representative about your project? YES/NO Contact: Mr Simon Buller The data will be stored in paper files and electronic database. This will be held on UCL laptop and associated back-up storages. All these devices are password protected.

H. ETHICS

H1	Are you applying to the UCL Research Ethics Committee? YES/NO Date of Ethics meeting: N/A
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I. REGISTRATION

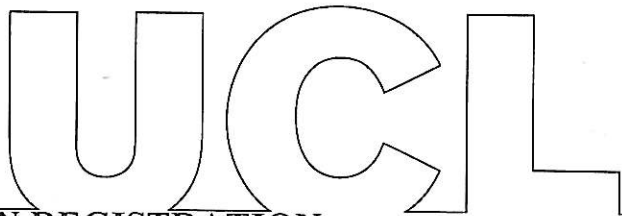
I1	Registration: Office use only:	
	UCL Data Protection Registration Number:	Data issued:

Further information

For more information and guidance on the UCL Research Committee, please visit
<http://ethics.grad.ucl.ac.uk/>

When all essential documents are ready to archive, contact the UCL Records Office by email at
records.office@ucl.ac.uk to arrange ongoing secure storage of your research records unless you have made specific alternative arrangements with your department, or funder.

For information on the UCL Records Management Service, please visit
<http://www.ucl.ac.uk/efd/recordsoffice/policy/records-transfer>



DATA PROTECTION REGISTRATION form 2

APPLICATION FOR INCLUSION OF A RESEARCH PROJECT

This form should be used to Register Research Projects that will be supported by UCL facilities. It should be completed in full and returned to the UCL Data Protection Officer before Data Collection commences.

If the Data has been collected from an organisation outside UCL then the Patient, or Subject, of the Data must have given their consent to both the collection of the Data and the transfer of the Data to UCL. A copy of the Patient Consent Form must be attached to this application. If you are not obtaining Patient Consent then an explanation must be attached.

DEPARTMENT	UCL Energy Institute
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Please return this form to: The UCL Data Protection Officer, The Records Office, South Junction, Wilkins Building, Gower Street London WC1E 6BT Or Email to: data-protection@ucl.ac.uk

Please allow five working days in which to receive your Data Protection Registration No.

Name of Principal Investigator (Student Supervisor)?	Dr David Shipworth	Name of Data Collector and User?	Miss Stephanie Gauthier
Please state here the Title of your research Project?	Mapping and Matching mental models of home thermal comfort systems		
Address for correspondence regarding this application.	Central house 14 Upper Woburn Place London WC1H 0NN		

Email Address:	s.gauthier@ucl.ac.uk
Telephone No.	020 3108 5978

Are you: Applying to the UCL Ethics Committee for Ethics Permission? (Yes/No)	No	How will the Data be stored? (Electronic Database/ Paper Files)	Electronic Database and Paper Files
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What Security Checks do you have in place? (Password on Electronic Database, Locked Filing Cabinets?)	Password on electronic database and Locked filing cabinets
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NB: Once the Research Project is completed, please contact the Records Office.

Email to: records.office@ucl.ac.uk to arrange ongoing secure storage of your research records

<http://www.ucl.ac.uk/efd/recordsoffice/policy/records-transfer/>

unless you have made specific alternative arrangements with your dept or with your funder

Have you registered your Database with your Department's Computer Representative? (Yes or No)	Yes (contact: Steve Smith)	Please state where the data will be held?	UCL laptop and associated back-up storage
Have you informed your Department's Data Protection Co-ordinator about your project? (Yes or No) NB: DP Officer will not be informing Dept DP Co-ordinator directly	Yes (contact: Kim Novelli)	How long will your project last?	Three and half years

The following are the standard Data Protection Registration Purposes and Descriptions. If your research is not covered by these please add the information at the end:

Please indicate using a (X) what is applicable to your research project

Personal Data will be collected from the following Data Subjects: (Who will you be collecting the data from)?

- ☒ Survey respondents, other persons assisting research
- ☐ Patients
- ☐ Patients families
- ☐ Employees, trainees, voluntary workers
- ☐ Employees of associated companies, organisations
- ☐ Employees of other organisations
- ☐ Recipients, customers or clients for goods or services (direct or indirect)
- ☐ Suppliers of goods or services (direct or indirect)
- ☐ Claimants, beneficiaries, payees
- ☐ Account holders
- ☐ Share and stock holders
- ☐ Partners, directors, other senior officers
- ☐ Employers
- ☐ Competitors
- ☐ Business or other contacts
- ☐ Advisers, consultants, professional and other experts
- ☐ Agents, other intermediaries
- ☐ Trustees
- ☐ Members, supporters a club, society, other institution
- ☐ Assignees, guarantors, other parties with legitimate contractual or business interest
- ☐ Donors and lenders
- ☐ Witnesses
- ☐ Complainants
- ☐ Offenders and suspected offenders
- ☐ Tenants
- ☐ Landlords, owners of property
- ☐ Correspondents and enquirers
- ☐ Self-employed persons
- ☐ Unemployed persons
- ☐ Retired persons
- ☐ Students
- ☐ Minors (if you are collecting data from minors, please include the Parent or Guardian Information Sheet and Consent form with your application)
- ☐ Applicants for permits, licences, registration
- ☐ Taxpayers, ratepayers
- ☐ Licence holders
- ☐ Vehicle Keepers
- ☐ Elected representatives, other holders of public office
- ☐ Authors, publishers, editors, artists, other creators
- ☐ Immigrants, foreign nationals
- ☐ Relatives, dependants, friends, neighbours, referees, associated, contacts of those ticked above

☐ Other: (specify):

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Tel: +44 (0)20 7679 2589 Fax: +44 (0)20 7679 2009
<http://www.ucl.ac.uk/efd/recordsoffice/data-protection/>

February 2008

Description of Personal Data to be collected: *(What data will you be collecting)?*

Identification data

- ☒ Personal identifiers
☐ Financial identifiers
☐ Identifiers issued by public bodies

Personal characteristics

- ☒ Personal details
☒ Physical description
☒ Habits
☒ Personality, character

Family circumstances

- ☒ Current marriage or partnership
☐ Marital history
☒ Details of other family, household members

- ☒ Other social contacts

Social circumstances

- ☒ Accommodation or housing
☒ Property, professions
☐ Immigration status
☒ Travel, movement details
☒ Leisure activities, interests
☒ Lifestyle
☐ Membership of voluntary, Charitable bodies
☐ Public offices held
☐ Licences, permits held
☐ Complaint, incident, accident details
☐ Court, tribunal, inquiry proceedings

Education, Skills, Profession

- ☐ Academic record
☒ Qualification and skills
☐ Membership of professional bodies
☐ Professional expertise
☐ Membership of committees
☐ Publications
☐ Student record

Employment details

- ☒ Current employment
☐ Recruitment details
☐ Termination details
☐ Career history

- ☐ Work record
☐ Health & safety record
☐ Trade union, staff association membership
☐ Payment, deductions
☐ Property held by employee
☐ Work management details
☐ Work assessment details
☐ Training record
☐ Security details

Financial details

- ☐ Income, assets, investments
☐ Liabilities, outgoings
☐ Loans, mortgages, credits
☐ Allowances, benefits, grants
☐ Insurance details
☐ Pension's details

Details of transactions

- ☐ Goods, services provided to the data subject
☐ Goods, services obtained from the data subject
☐ Financial transactions
☐ Compensation

Business information

- ☐ Business activities of the data subject
☐ Agreements, contracts
☐ Trading licences held

Health and other classes

- ☒ Physical health record
☐ Mental Health Record
☒ Disabilities, infirmities
☐ Dietary and other special health requirements
☐ Sexual life
☐ Racial, ethnic origin
☐ Motoring convictions
☐ Other convictions
☐ Criminal intelligence
☐ Political opinions
☐ Political party membership
☐ Support for pressure groups
☐ Religious beliefs
☐ Other: data class (specify):

The Results of the Research will be Disclosed to:

Individuals or Organisations directly associated with the Data Subjects

- ☒ The Data Subjects themselves
- ☐ Family, relatives, guardians, trustees
- ☐ Other members of their households, friends, neighbours
- ☐ Employers - past, current or prospective
- ☐ Employees, agents
- ☐ Colleagues, business associates
- ☐ Legal representatives
- ☐ Financial representatives
- ☐ Legal representatives
- ☐ Financial representatives
- ☐ Doctors, Dentists, other advisers
- ☐ Social, spiritual, welfare, advice workers
- ☐ Other professional advisers
- ☐ Landlords

Individuals or Organisations directly associated with the Data User

- ☐ Research Sponsors
- ☐ Funding Agencies
- ☐ Ethics Committees
- ☐ Members, including shareholders
- ☐ Other companies in the same group
- ☐ Employees, agents
- ☐ Recipients, customers, clients for goods or services
- ☐ Claimants, beneficiaries, assignees, payees
- ☐ Suppliers, providers of goods or services
- ☐ Persons making any enquiry or complaint
- ☐ Tenants
- ☐ Other: (specify):

Organisation or individuals (general description)

Central Government

- ☐ Inland Revenue
- ☐ Customs & Excise
- ☐ Driver & Vehicle Licensing Centre (DVLC)
- ☐ Department of Education & Sciences (DES)
- ☐ Departments of Health and/or Social Security
- ☐ Department of Employment
- ☐ Home Office
- ☐ Ministry of Defence, including armed forces
- ☐ Department of Constitutional Affairs
- ☐ Other central government, including Scottish
- ☐ Welsh & Northern Ireland Offices
- ☐ Other (specify):

Local Government

- ☐ Education department
- ☐ Housing department
- ☐ Social Services department

- ☐ Electoral registration, Assessment,
- ☐ Valuation departments

Other public bodies

- ☐ Other public bodies not elsewhere specified
- ☐ Foreign governments and authorities (specify):

Justice

- ☐ Police forces
- ☐ Prosecuting authorities
- ☐ Other statutory law enforcement agencies, Investigating bodies
- ☐ The courts
- ☐ Judges, magistrates
- ☐ Prison service
- ☐ Probation service

Health & Social welfare

- ☐ Health authorities, family practitioners committees
- ☐ or Family Health Service Authorities
- ☐ Hospitals, nursing homes
- ☐ Registered medical practitioners
- ☐ Registered dental practitioners
- ☐ Nurses, midwives, health visitors
- ☐ Other health care agencies, practitioners (specify):
- ☐ Social welfare agencies, practitioners (specify):

Other

- ☐ Media
- ☐ Public utilities
- ☐ Banks
- ☐ Building societies
- ☐ Insurance companies
- ☐ Other financial organisations (specify):
- ☐ Accountants & auditors
- ☐ Lawyers
- ☐ Credit reference agencies
- ☐ Debt collection, tracing agencies
- ☐ Employment, recruitment agencies
- ☐ Private detective agencies, security organisations
- ☐ Trade, employers associations
- ☐ Trade unions, staff associations
- ☐ Professional bodies
- ☐ Voluntary, charitable, religious organisations or associations
- ☐ Political organisations
- ☐ Education or training establishments, examining bodies
- ☐ Survey or research organisations, workers
- ☐ Providers of publicly available information, including public libraries, press and media
- ☐ Providers of privately available information and databanks
- ☐ Traders in personal data
- ☐ Other organisation or individuals (specify):
- ☐ Other: (specify):

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 Tel: +44 (0)20 7679 2589 Fax: +44 (0)20 7679 2009
<http://www.ucl.ac.uk/efd/recordsoffice/data-protection/>

February 2008

Will the Results of your Research be published in an Academic Journal or other Publication? (Yes or No)	Yes
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Please note that if you do publish the results of your Research they must not contain data by which an individual can be identified.

<p>B4. Overseas Transfer</p> <p>The Eighth Data Protection Principle. Personal data shall not be transferred to a country or territory outside the European Economic Area unless that country or territory ensures an adequate level of protection for the rights and freedoms of data subjects in relation to the processing of personal data.</p> <p>The European Economic Area consists of the twenty seven member states of the European Union together with Iceland, Liechtenstein, Norway and the States of Guernsey and Jersey. Data may be transferred within the European Economic Area without restrictions.</p>	<p>Are you collecting the Data in a country outside of the EEA? Yes <input type="checkbox"/> No <input checked="" type="checkbox"/></p> <p><i>Please attach a copy of the Data Protection Registration in that country</i></p> <p>Do you intend to transfer the Data to any other country or territory? Yes <input type="checkbox"/> No <input checked="" type="checkbox"/></p> <p><i>Please give details and attach a copy of your agreement with the recipient.</i></p>
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This form will be returned to you with the appropriate UCL Data Registration References, which you may quote on your Ethics Application Form, or any other related forms.

UCL Data Protection Registration Reference No:	26364106/ 2010/10/39	SECTION:	19, Research: Social Research
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Any queries regarding this form please contact: Tel: 020 76790166 (UCL ext.30166)

RISK ASSESSMENT FORM

FIELD / LOCATION WORK

The Approved Code of Practice - Management of Fieldwork should be referred to when completing this form
<http://www.ucl.ac.uk/estates/safetynet/guidance/fieldwork/acop.pdf>

DEPARTMENT/SECTION UCL ENERGY INSTITUTE

LOCATION(S) CENTRAL HOUSE, 14 UPPER WOBURN PLACE, LONDON WC1H 0NN

PERSONS COVERED BY THE RISK ASSESSMENT Stephanie Gauthier

BRIEF DESCRIPTION OF FIELDWORK Mapping people's responses to thermal discomfort in dwelling

Consider, in turn, each hazard (white on black). If **NO** hazard exists select **NO** and move to next hazard section. If a hazard does exist select **YES** and assess the risks that could arise from that hazard in the risk assessment box. **Where risks are identified that are not adequately controlled they must be brought to the attention of your Departmental Management who should put temporary control measures in place or stop the work. Detail such risks in the final section.**

ENVIRONMENT

e.g. location, climate, terrain, neighbourhood, in outside organizations, pollution, animals.

The environment always represents a safety hazard. Use space below to identify and assess any risks associated with this hazard

Examples of risk: adverse weather, illness, hypothermia, assault, getting lost.
Is the risk high / medium / low ?

Low

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- | | |
|-------------------------------------|---|
| <input type="checkbox"/> | work abroad incorporates Foreign Office advice |
| <input type="checkbox"/> | participants have been trained and given all necessary information |
| <input type="checkbox"/> | only accredited centres are used for rural field work |
| <input checked="" type="checkbox"/> | participants will wear appropriate clothing and footwear for the specified environment |
| <input type="checkbox"/> | trained leaders accompany the trip |
| <input type="checkbox"/> | refuge is available |
| <input checked="" type="checkbox"/> | work in outside organisations is subject to their having satisfactory H&S procedures in place |
| <input type="checkbox"/> | OTHER CONTROL MEASURES: please specify any other control measures you have implemented: |

EMERGENCIES

e.g. fire, accidents

Where emergencies may arise use space below to identify and assess any risks

Examples of risk: loss of property, loss of life

Low

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- | | |
|-------------------------------------|---|
| <input type="checkbox"/> | participants have registered with LOCATE at http://www.fco.gov.uk/en/travel-and-living-abroad/ |
| <input type="checkbox"/> | fire fighting equipment is carried on the trip and participants know how to use it |
| <input checked="" type="checkbox"/> | contact numbers for emergency services are known to all participants |
| <input type="checkbox"/> | participants have means of contacting emergency services |
| <input type="checkbox"/> | participants have been trained and given all necessary information |
| <input type="checkbox"/> | a plan for rescue has been formulated, all parties understand the procedure |
| <input type="checkbox"/> | the plan for rescue /emergency has a reciprocal element |
| <input type="checkbox"/> | OTHER CONTROL MEASURES: please specify any other control measures you have implemented: |

EQUIPMENT	Is equipment used?	Yes	If 'No' move to next hazard If 'Yes' use space below to identify and assess any risks
e.g. clothing, outboard motors.	Examples of risk: inappropriate, failure, insufficient training to use or repair, injury. Is the risk high / medium / low ?		
Low			

CONTROL MEASURES	Indicate which procedures are in place to control the identified risk
<input type="checkbox"/>	the departmental written Arrangement for equipment is followed
<input checked="" type="checkbox"/>	participants have been provided with any necessary equipment appropriate for the work
<input type="checkbox"/>	all equipment has been inspected, before issue, by a competent person
<input checked="" type="checkbox"/>	all users have been advised of correct use
<input type="checkbox"/>	special equipment is only issued to persons trained in its use by a competent person
<input type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

LONE WORKING	Is lone working a possibility?	Yes	If 'No' move to next hazard If 'Yes' use space below to identify and assess any risks
e.g. alone or in isolation lone interviews.	Examples of risk: difficult to summon help. Is the risk high / medium / low?		
Low			

CONTROL MEASURES	Indicate which procedures are in place to control the identified risk
<input type="checkbox"/>	the departmental written Arrangement for lone/out of hours working for field work is followed
<input type="checkbox"/>	lone or isolated working is not allowed
<input type="checkbox"/>	location, route and expected time of return of lone workers is logged daily before work commences
<input checked="" type="checkbox"/>	all workers have the means of raising an alarm in the event of an emergency, e.g. phone, flare, whistle
<input type="checkbox"/>	all workers are fully familiar with emergency procedures
<input checked="" type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

Contact arrangement procedure as follow:

1. Visit log to be issued, including visit and participant details;
2. Contact arrangement procedure via mobile phone text to be followed:
 - 2.1 the researcher will text the supervisor upon arrival;
 - 2.2 the researcher will set an alarm and text the supervisor 1.5h after arrival:
 - 2.2.1 to confirm that the visit did finish and that all is fine;
 - 2.2.2 to extend the visit time by 1h;

2.3 if the visit was extended, the researcher will set an alarm and text the supervisor 2.5h after arrival:

2.3.1 to confirm that the visit did finish and that all is fine;

2.3.2 to extend the visit time by 1h;

(step 2.3 may be repeated until the visit finishes)

ILL HEALTH

e.g. accident, illness, personal attack, special personal considerations or vulnerabilities.

The possibility of ill health always represents a safety hazard. Use space below to identify and assess any risks associated with this Hazard.

Examples of risk: injury, asthma, allergies. Is the risk high / medium / low?

Low

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- ☐ an appropriate number of trained first-aiders and first aid kits are present on the field trip
- ☐ all participants have had the necessary inoculations/ carry appropriate prophylactics
- ☐ participants have been advised of the physical demands of the trip and are deemed to be physically suited
- ☐ participants have been adequate advice on harmful plants, animals and substances they may encounter
- ☐ participants who require medication have advised the leader of this and carry sufficient medication for their needs
- ☐ OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

TRANSPORT

e.g. hired vehicles

Will transport be required

NO

YES

Move to next hazard

Use space below to identify and assess any risks

Examples of risk: accidents arising from lack of maintenance, suitability or training

Is the risk high / medium / low?

Low

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- ☒ only public transport will be used
- ☒ the vehicle will be hired from a reputable supplier
- ☐ transport must be properly maintained in compliance with relevant national regulations
- ☐ drivers comply with UCL Policy on Drivers http://www.ucl.ac.uk/hr/docs/college_drivers.php
- ☐ drivers have been trained and hold the appropriate licence
- ☐ there will be more than one driver to prevent driver/operator fatigue, and there will be adequate rest periods
- ☐ sufficient spare parts carried to meet foreseeable emergencies
- ☐ OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

DEALING WITH THE PUBLIC

e.g. interviews, observing

Will people be dealing with public

Yes

If 'No' move to next hazard

If 'Yes' use space below to identify and assess any risks

Examples of risk: personal attack, causing offence, being misinterpreted. Is the risk high / medium / low?

Low

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- ☐ all participants are trained in interviewing techniques
- ☐ interviews are contracted out to a third party
- ☐ advice and support from local groups has been sought
- ☒ participants do not wear clothes that might cause offence or attract unwanted attention
- ☐ interviews are conducted at neutral locations or where neither party could be at risk
- ☐ OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

WORKING ON OR NEAR WATER

e.g. rivers, marshland, sea.

Will people work on or near water?

No

If 'No' move to next hazard

If 'Yes' use space below to identify and assess any risks

Examples of risk: drowning, malaria, hepatitis A, parasites. Is the risk high / medium / low?

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- ☐ lone working on or near water will not be allowed
- ☐ coastguard information is understood; all work takes place outside those times when tides could prove a threat
- ☐ all participants are competent swimmers
- ☐ participants always wear adequate protective equipment, e.g. buoyancy aids, wellingtons
- ☐ boat is operated by a competent person
- ☐ all boats are equipped with an alternative means of propulsion e.g. oars
- ☐ participants have received any appropriate inoculations
- ☐ OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

MANUAL HANDLING (MH)

e.g. lifting, carrying, moving large or heavy equipment, physical unsuitability for the task.

Do MH activities take place?

No

If 'No' move to next hazard

If 'Yes' use space below to identify and assess any risks

Examples of risk: strain, cuts, broken bones. Is the risk high / medium / low?

CONTROL MEASURES

Indicate which procedures are in place to control the identified risk

- ☐ the departmental written Arrangement for MH is followed
- ☐ the supervisor has attended a MH risk assessment course
- ☐ all tasks are within reasonable limits, persons physically unsuited to the MH task are prohibited from such activities
- ☐ all persons performing MH tasks are adequately trained
- ☐ equipment components will be assembled on site
- ☐ any MH task outside the competence of staff will be done by contractors
- ☐ OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

SUBSTANCES	Will participants work with substances	No	If 'No' move to next hazard If 'Yes' use space below to identify and assess any risks
<i>e.g. plants, chemical, biohazard, waste</i>	Examples of risk: ill health - poisoning, infection, illness, burns, cuts. Is the risk high / medium / low?		

CONTROL MEASURES	Indicate which procedures are in place to control the identified risk
<input type="checkbox"/>	the departmental written Arrangements for dealing with hazardous substances and waste are followed
<input type="checkbox"/>	all participants are given information, training and protective equipment for hazardous substances they may encounter
<input type="checkbox"/>	participants who have allergies have advised the leader of this and carry sufficient medication for their needs
<input type="checkbox"/>	waste is disposed of in a responsible manner
<input type="checkbox"/>	suitable containers are provided for hazardous waste
<input type="checkbox"/>	OTHER CONTROL MEASURES: please specify any other control measures you have implemented:

OTHER HAZARDS	Have you identified any other hazards?	No	If 'No' move to next section If 'Yes' use space below to identify and assess any risks
<i>i.e. any other hazards must be noted and assessed here.</i>	Hazard:		
	Risk: is the risk <input type="text"/>		

CONTROL MEASURES	Give details of control measures in place to control the identified risks

Have you identified any risks that are not adequately controlled?	<table border="1"> <tr> <td>NO</td> <td><input checked="" type="checkbox"/></td> <td>Move to Declaration</td> </tr> <tr> <td>YES</td> <td><input type="checkbox"/></td> <td>Use space below to identify the risk and what action was taken</td> </tr> </table>	NO	<input checked="" type="checkbox"/>	Move to Declaration	YES	<input type="checkbox"/>	Use space below to identify the risk and what action was taken
NO	<input checked="" type="checkbox"/>	Move to Declaration					
YES	<input type="checkbox"/>	Use space below to identify the risk and what action was taken					

Is this project subject to the UCL requirements on the ethics of Non-NHS Human Research?

If yes, please state your Project ID Number

For more information, please refer to: <http://ethics.grad.ucl.ac.uk/>

DECLARATION	The work will be reassessed whenever there is a significant change and at least annually. Those participating in the work have read the assessment.
Select the appropriate statement:	
<input checked="" type="checkbox"/>	I the undersigned have assessed the activity and associated risks and declare that there is no significant residual risk
<input checked="" type="checkbox"/>	I the undersigned have assessed the activity and associated risks and declare that the risk will be controlled by the method(s) listed above

NAME OF SUPERVISOR

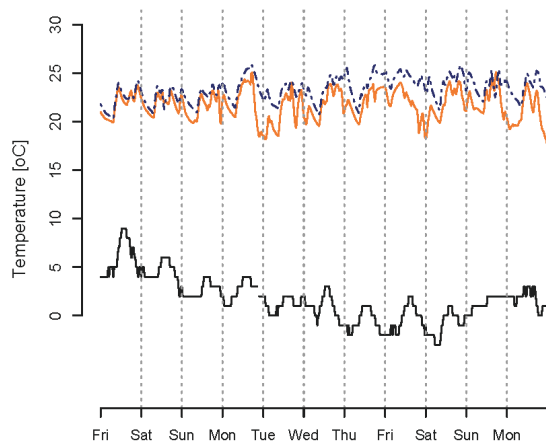
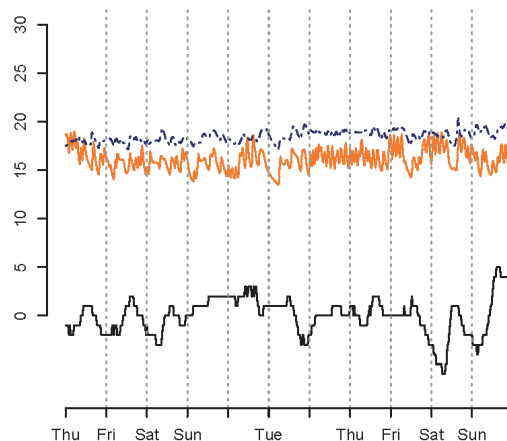
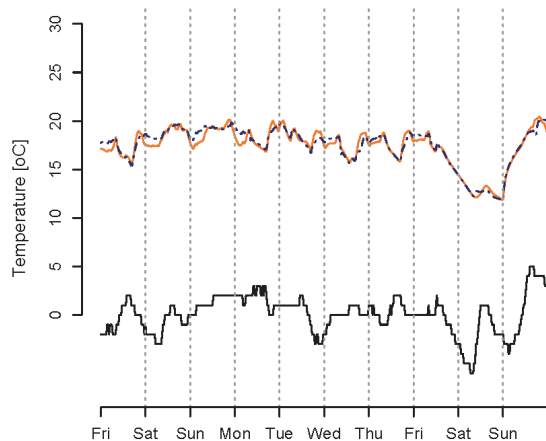
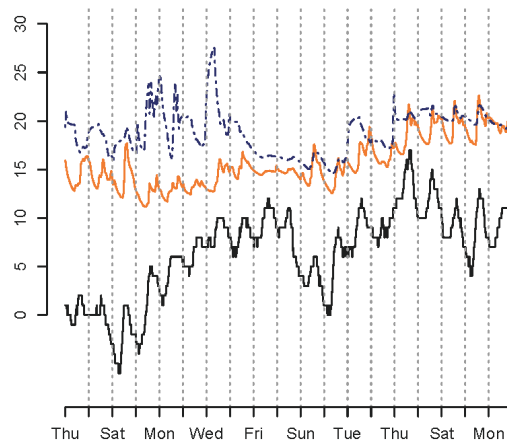
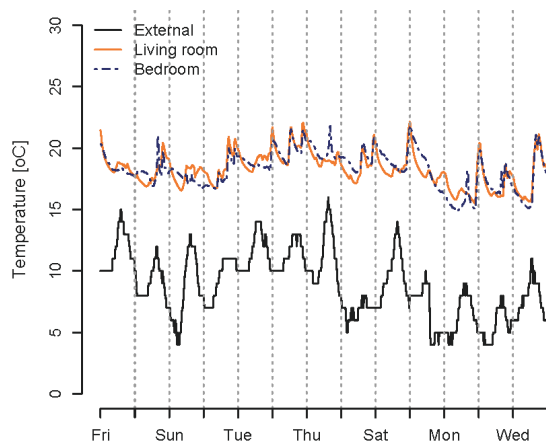
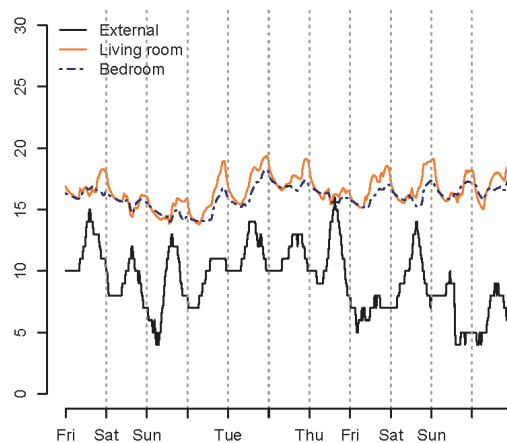
SIGNATURE OF SUPERVISOR

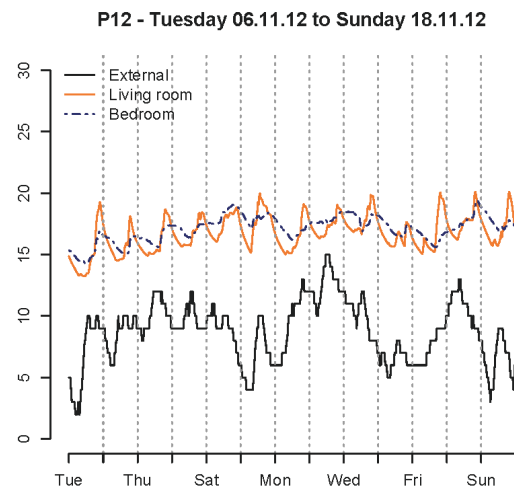
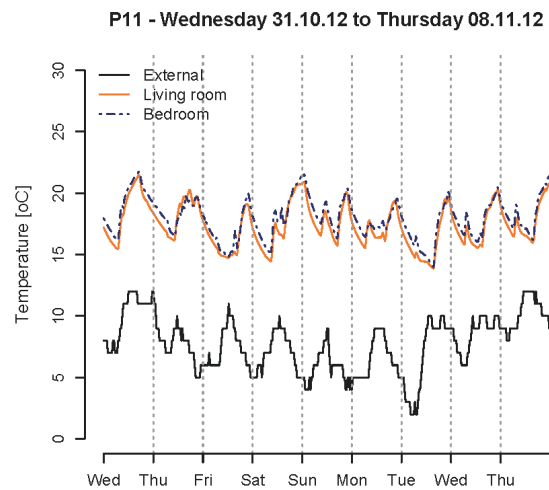
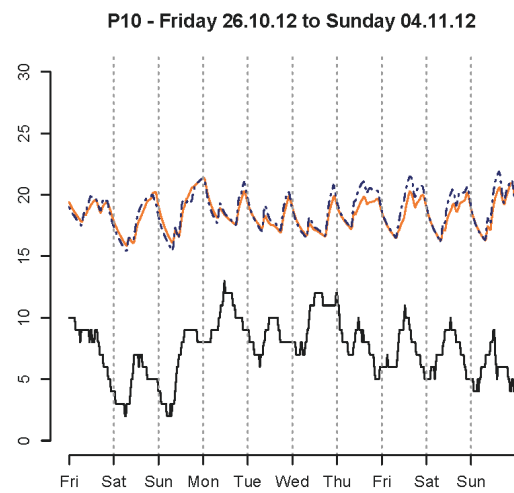
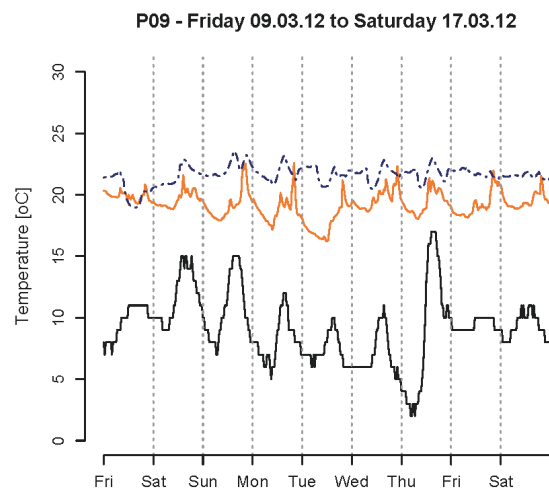
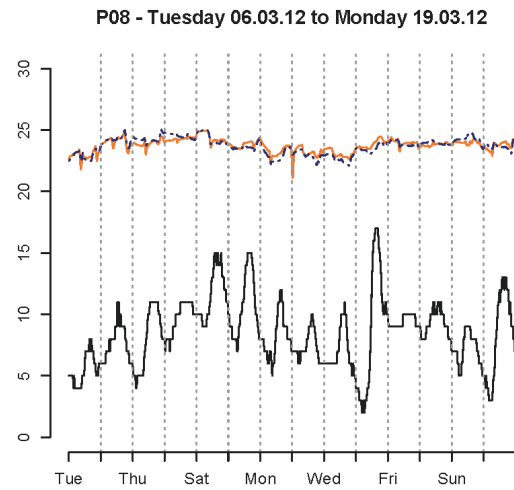
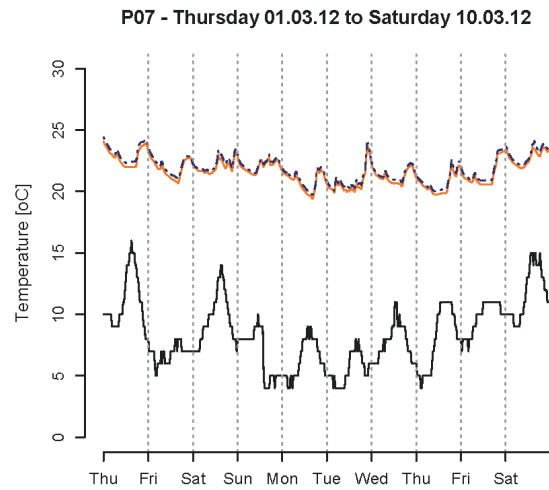
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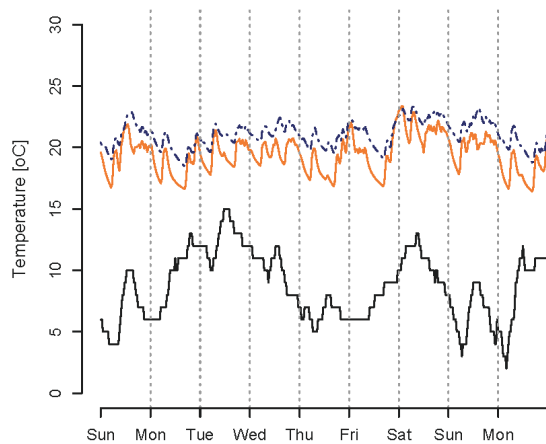
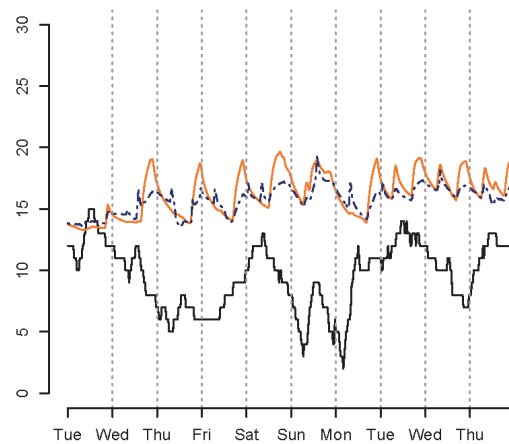
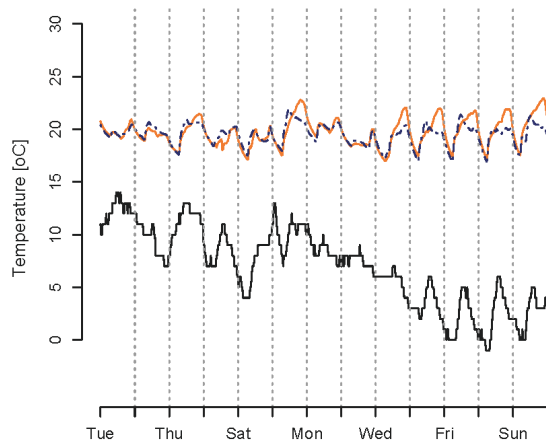
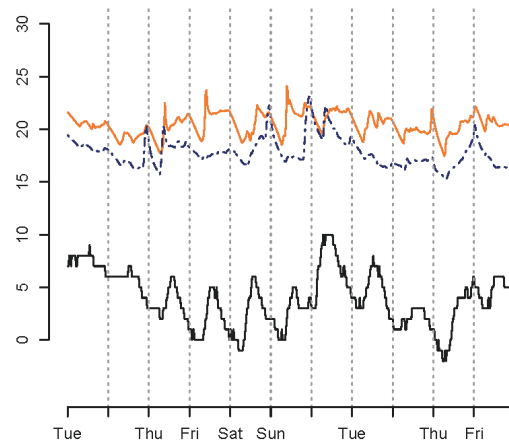
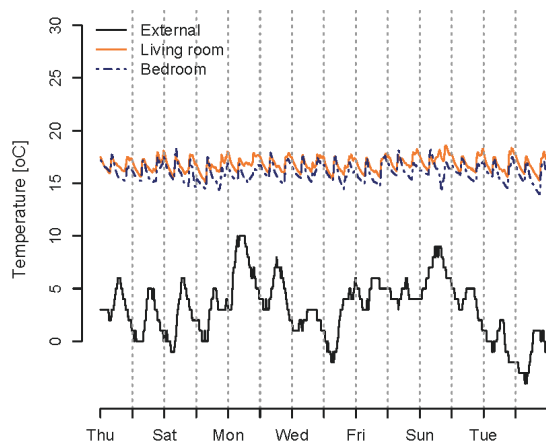
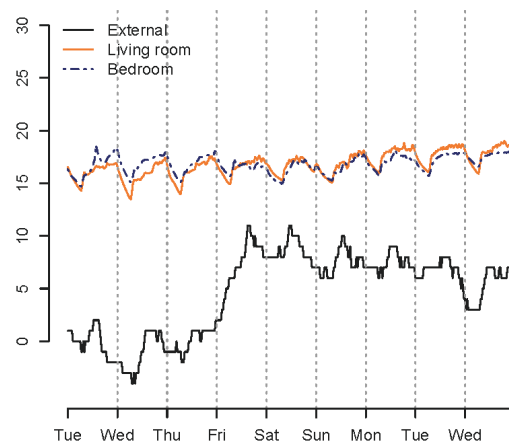
Appendix C

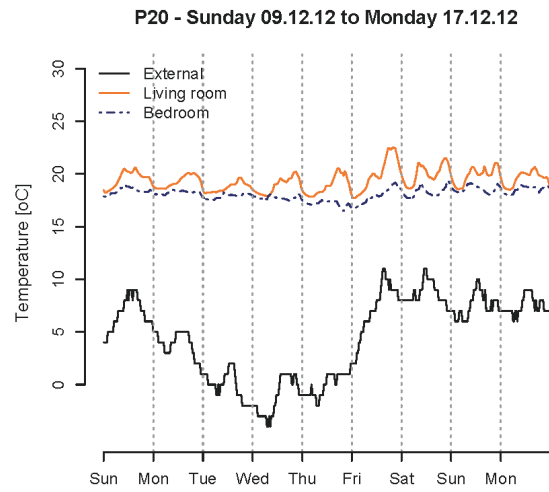
Main study external and internal temperatures

External temperatures and internal monitored temperatures in living rooms and bedrooms during the main study for all participants.

P01 - Friday 27.01.12 to Monday 06.02.12**P02 - Thursday 02.02.12 to Sunday 12.02.12****P03 - Friday 03.02.12 to Sunday 12.02.12****P04 - Thursday 09.02.12 to Monday 27.02.12****P05 - Friday 24.02.12 to Wednesday 07.03.12****P06 - Friday 24.02.12 to Monday 05.03.12**



P13 - Sunday 11.11.12 to Monday 19.11.12**P14 and P15 - Tuesday 13.11.12 to Thursday 22.11.12****P16 - Tuesday 20.11.12 to Sunday 02.12.12****P17 - Tuesday 27.11.12 to Friday 07.12.12****P18 - Thursday 29.11.12 to Wednesday 12.12.12****P19 - Tuesday 11.12.12 to Wednesday 19.12.12**



Appendix D

Papers from this thesis

D.1 Book chapter

1. Ucci, M., Gauthier, S., Mavrogianni, A. Thermal Comfort: Assessment, Psychosocial Aspects and Health Impacts. A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health, and Operational Performance. Editors: Mumovic, D., Santamouris, M. Earthscan, London. (Submitted 9th May 2014).

D.2 Peer-reviewed journal papers

1. Gauthier, S., Shipworth, D. (2015). Behavioural responses to cold thermal discomfort, Building Research & Information, 43:3, pp.355-370.
2. Spataru, C. and Gauthier, S. (2013). How to monitor people smartly to help reducing energy consumption in buildings? Architectural Engineering and Design Management, 10(1-2), pp.60-78.

D.3 Peer-reviewed conference papers published in journals

1. Gauthier, S., Shipworth, D. (2013). Review of Methods to Map People Daily Activity: Application for Smart Homes. In A. Hakansson et al., eds. Sustainability in Energy and Buildings, Springer Berlin Heidelberg, Volume 22, pp. 401-411.
2. Gauthier, S. (2012). Mapping Occupants Thermal Discomfort Responses in Households Using SenseCam. In N. MSirdi et al., eds. Sustainability in Energy and Buildings, Springer Berlin Heidelberg, Volume 12, pp. 437-445.

D.4 Peer-reviewed conference papers published in conference proceedings

1. Gauthier, S. Shipworth, D. (2014). Generating empirical probabilities of metabolic rate and clothing insulation values in field studies using wearable sensors. Conference proceedings: 13th International Conference on Indoor Air Quality and Climate, 7-12 July 2014, Hong Kong.
2. Gauthier, S. Shipworth, D. (2014). Variability of thermal stratification in naturally ventilated residential buildings. Conference proceedings: 2014 Building Simulation and Optimization Conference. 23-24 June 2014, London, UK.
3. Gauthier, S. Shipworth, D. (2014). The gap between what is said and what is done: a method for distinguishing reported and observed responses to thermal discomfort. Conference proceedings: 8th Windsor Conference: Counting the Cost of Comfort in a changing world Cumberland Lodge, Windsor, UK, 10-13 April 2014. Network for Comfort and Energy Use in Buildings. London, UK.
4. Gauthier, S. M. (2013). The role of environmental and personal variables in influencing thermal comfort indices used in building simulation. Conference proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France.
5. Gauthier, S. Shipworth, D. (2012). Predictive thermal comfort model: Are current field studies measuring the most influential variables? Conference proceedings: 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World, Cumberland Lodge, Windsor, UK, 12-15 April 2012. Network for Comfort and Energy Use in Buildings. London, UK.
6. Gauthier, S. M., (2011). What Are People's Responses to Thermal Discomfort? Sensing Clothing and Activity Levels Using SenseCam. UC Berkeley: Behavior, Energy and Climate Change Conference, USA.
7. Gauthier, S., (2011). Understanding the dynamics of residential energy consumption: Mapping occupants thermal discomfort responses. Conference proceedings: ECEEE 2011, Summer Study, Energy efficiency first: The foundation of a low-carbon society. ABA Intercopy, Stockholm, Sweden.